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Mortars in Old Buildings and in Masonry Conservation

A Historical and Practical Treatise

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Errata

Page 1, line 20: For thoe Read those
Page 3, line 5: For immersion Read setting while immersed
Page 3, line 32: For produe Read produce
Page 4, line 14: For Chamouni Read Chamouni, France
Page 9, line 2: For to enable Read that enables
Page 9, line 28: For Hydraulic Read Hydraulique
Page 21, line 31: For inferiority Read quality
Page 22, line 20: For and this component has been attributed, in part, to the cause of Read and to this component has been attributed, in part,
Page 27, line 13: For decreases Read increases
Page 34, line 19: For on that Read on the
Page 44, line 9: For 1822 Read 1812
Page 65, line 5: For showen Read shown
Page 77, line 32: For te Read the
Page 158, line 3: For 1:1:3 Read 1:1:6
Page 183, line 6-7: For immediate strain) Read immediate) strain
Page 250, line 17: For strank Read shrank

<u>Table of Contents</u>

Abstract

This thesis examines the subject of mortar, with the aim of presenting information that will assist in the repair of historic masonry structures. A historical examination of two primary mortar ingredients, lime and cement, together with a discussion of other ingredients, establishes a basis for further scientific study. Analysis of observed case studies yields hypotheses on mortar behavior. A survey of published literature discloses much information about creep, a vital element of mortar behavior. However, because in most of the previous research the creep measurements were made on brickwork or blockwork piers, an experimental program was devised to measure the shrinkage and creep in mortars alone, using a range of seven mortar mixes. Some of the findings of D. Lenczner and A.M. Neville have been confirmed, and considerable additional information concerning creep and shrinkage in mortars has been obtained. Results indicate that the quantity of lime in a mortar is related to shrinkage and creep: the richer the mortar is in lime, the higher the values for creep and the lower the values for shrinkage. The laboratory data can aid in the future selection of the proper mortar for repairs to masonry buildings.

Chapter 1: Theories on Lime

Introduction

From the late eighteenth century onwards, treatises began to contain large sections devoted to experiments conducted on mortar ingredients. Many were written as an outlet to dispute other contemporary authors' theories. However, they have become a valuable source in that they give insight into previous beliefs and how they were arrived at. Furthermore, they laid the groundwork from which research today stems, and this research, aided by twentieth-century technology, allows for a better understanding of mortars and their components.

Materials--their use, and their composition--were the main topics of these eighteenth-century treatises. The objective was to determine, through experimentation, what produced a good, strong, durable mortar. A full understanding of the ingredients of mortars is still necessary in specifying mortars today. By examining these old treatises and laws, followed by specific experimenting, proportions and the proper components of a mortar can be adjusted to achieve appropriate mortars for use today and in the future.

Three of the main issues that were disputed in the mid-eighteenth through mid-nineteenth centuries were: 1) the chemistry of lime and what in it determined its hydraulicity; 2) the quality of mortar acquired by the addition of additives, either thoe prepared by man, such as iron filings, or those of natural origin such as pozzolana; and 3) the storage of mortar materials and its effect on the ultimate use. Disputes between scientists continued for a century (1756 - 1855), with the advent of Roman cement and Portland cement causing further testing and discussion as to the quality of the new cement, justifying the exclusion of the old lime mortar. To understand the minds of such men as Louis J. Vicat, and how they arrived at various mortar theories, their treatises must be examined.

Hydraulic Limes

The main theory or rule set down by Vitruvius, Pliny, and other Romans was that the strongest lime was pure white and made from the hardest limestone.[1] Until John Smeaton, architects such as Palladio, Alberti, Scamozzi, and de l'Orme all followed the teachings and theories of Vitruvius. Some men such as Bernard Forest de Belidor and George Semple were still using this theory as late as 1729 and 1780. While mortars may have contained fossiciae, powdered tiles, or pozzolana, the lime used was strictly white, and ground from a hard limestone. In his 1729 treatise, La Science des Ingenieurs, Belidor stated that white marble proved the most successful in yielding a good lime. Tests conducted on clay had shown that this material produced a weak lime.[2] He concluded that 'hard' and 'white' were both necessary components in a good limestone.

Although working during the same period as Belidor and Semple, Smeaton was the first since Vitruvius to experiment with lime and mortars on a large scale, and first to question many of the previously-accepted theories concerning materials and their reaction in a mortar. In 1756 his observations and tests brought him very close to understanding which components of limes made them useful in a mortar.[3] He began his tests during the preliminary days of the construction of the Eddystone lighthouse. His aim was to make a mortar that would withstand repeated washing with salt water.

Smeaton started by determining which components, preferably obtained within Great Britain, would help create a strong, durable mortar. He procured a variety of limes and pozzolanas, and made cubic samples of various proportions. His tests included nine British limes of different qualities and some imported pozzolanas. The results obtained were not governed by the initial hardness of the limestone. The softest white chalk produced the same strength in a mortar as did the hardest white marble. He went one step further in these tests and also showed that the strongest mortars were not produced by the whitest limes: the color was immaterial. Of the nine limes Smeaton used, some were white and others were blue (such as Blue Lias lime) or brown. Yet, all produced equally strong limes. In essence, Smeaton disproved the rule set down by Vitruvius and others more than 2000 years before.

After the tests concerning composition, Smeaton analyzed some of the limes chemically. He discovered that those limes that were hydraulic—capable of immersion in water—contained a very high clay content. The addition of a clay to a pure lime was not sufficient to render it hydraulic; they first had to be burned to acquire the necessary results of hardening. Unfortunately, Smeaton was more concerned with the outcome: the mortar and its reaction with a building material. He overlooked the more important element in making a good mortar, the clay, and conducted no further tests in this direction, despite his initial work contradicting some of Belidor's. He simply concluded his research on clay by saying: "For some reason or other, when a limestone is intimately mixed with a proportion of clay,...it is made to act more strongly as a Cement."[4]

Smeaton spent considerably more time studying elements that could be added to a slaked-lime mortar to allow for a set under water. He noted that the equal addition of pôzzolana or 'ferruginous' substances such as minion to lime produced the required results.[5] His stress on the presence of ferruginous substances no doubt led other scientists to attribute to the presence of iron oxide the hydraulicity of limes.[6]

Tobern O. Bergmann and Baron Louis B. Guyton de Morveau were two scientists who followed Smeaton and conducted tests on the ferruginous aspects of lime, rather than on its clay aspects. Bergmann used black limestone to run tests on the hydraulicity of limes, and in so doing aided Smeaton in disproving Vitruvius's theory by producing a suitable lime for under water, yielded from black stone. He also attributed the black color in the limestone to manganese, and believed that it was this element that gave lime its strength. In the hydraulic limes analyzed by Bergmann and Guyton de Morveau, they regarded manganese as the ferruginous substance necessary to produe a hydraulic lime. Both men published treatises to this effect within five years of each other: Guyton de Morveau's _Journal de Physique_ in 1774 and Bergmann's _Opuscula Physica et Chemica_ in 1779.

The paths of future experimentation diverged by the end of the eighteenth century. Some men, by pinpointing exactly what in the clay gave lime superior qualities over common lime, strove to develop the theory that clay made lime hydraulic. Others, such as Bergmann, tried to substantiate their own findings and theories, which they were sure were right. Table 1 provides a visual reference to the men involved in the study of lime and which ingredient their tests convinced them was the reason for the hydraulicity of lime.

Horace-Benedict de Saussure, a follower of the clay theory, almost immediately set out to disprove Bergmann and Guyton de Morveau. In 1780 he published Voyages dans les Alpes, in which he stated that it was calcined clay, not the action of manganese, that produced water-setting properties in lime. He observed a mortar composed of manganese-free lime from Chamouni set under water. This observation, and de Saussure's own findings, were substantiated further when a Swedish lock, built with mortar composed of lime and manganese oxide, failed completely. "M. Pack, Professor of the Arts and Sciences at Stockholm, informed me that, in reliance upon M. Bergmann, they had in Sweden constructed a whole lock with mortar of rich lime and the peroxide of manganese, but that the wretched condition of the masonry had necessitated its demolition."[7] Bergmann and Guyton de Morveau's theory was finally proven wrong.

Other men also began detailed experimentation on lime, following the clay theory proposed by Smeaton. Vicat, Descotils, Parandier, Dumas, Treussart and John expanded Smeaton's work in an effort to pinpoint the source of hydraulicity in clay. Vicat was the leader in this field. In testing a variety of limestones he also found color to be immaterial, and high levels of clay to be important. One yellow limestone produced excellent results in a mortar, and this strength as well as color was attributed to the iron particles within the stone. These experiments further disproved Vitruvius's theory.

Vicat's tests soon proved that the clays within a lime had to contain silica and alumina before hydraulic qualities were obtained. The amounts of these two components and a selection of other ingredients such as iron or magnesia determined how strong the lime would be under

Clay	Iron Oxides	Manganese	Silica
Smeaton (1756) Higgins (1780) De Saussure (1780) Vitalis (1806) Vicat (1810+) Followers of Vicat: Thenard (1815) Descotils (1818+) Dumas (1818+) Petot (1818) St. Leger (1818+) Sgauzin (1818+) John (1819) Raucourt de Charleville (1822) Berthier (1824) Hassenfraz (1825) Girard de Caudemberg (1826) Treussart (1829) Pasley (1830) Gay Lussac (1837) Burnell (1850)	Smeaton (1756) Treussart (1829)	Guyton de Morveau (1774) Bergmann (1779)	Descotils (1813)

Magnesia	Hard/White Limestones	Arenes
Vaillant Chatoney Rivot Parandier (1830+) Berthier (1830-2) Pasley (1830) Vicat (1837)	Belidor (1729) Semple (1780)	Girard de Caudemberg (1826) Treussart (1829)

Soda/Potash	Alkali Silicate	By a Specific Method
Treussart (1829) Kuhlmann (1855)	Fuches (1818) Kuhlmann (1841)	Loriot (1765) De la Faye (1777) St. Fond (1778)

Table 1: Ingredients To Produce a Hydraulic Lime

Dates are given after the men's names to indicate when each man experimented on the specific ingredient under which he is listed. The dating further helps to show when certain men like Descotils and Kuhlmann cast aside their original theories in favor of a new source for the hydraulicity of lime. Men who appear in several columns and show the same date by their names either had several theories going at the same time (e.g. Smeaton) or believed that two ingredients worked together to produce a hydraulic lime (e.g. Pasley).

water. Vicat made up mortar samples containing 1 part of rich lime to 2 parts of silica or alumina oxide, and dried them in a variety of ways.[8] Using the test he invented, and which is today known as the Vicat Needle test, he was able to determine how quickly and how strongly the oxides combined with the lime. The experiments showed that lime and alumina did not harden sufficiently to produce a hydraulic lime, but that lime and silica did yield an acceptable hydraulic lime. To check these results, Vicat also analyzed several old mortars of known superior durability to discover if the ingredients included large quantities of silica and alumina. He found high levels of silica and magnesia and concluded that silica was very important in a hydraulic lime. However with the addition of alumina, and perhaps magnesia or iron, an even stronger, more durable hydraulic mortar could be manufactured.[9]

Vicat summarized his work by creating five classes of limes based on their clay content.[10] 'Rich' limes contained 1 - 6%; 'poor' limes had 3 - 15%; 'moderately hydraulic' limes contained 8 - 12%; and 'hydraulic' limes had 20 - 30% with half of that being silica. The fifth category was entitled 'eminently hydraulic' limes and differed from the fourth class in that the amount of silica was 11 - 25%. Later he created four more classifications dealing with other materials' reaction with lime, in particular the reaction between clay and lime. The classes were simply: 'very energetic' lime; 'simply energetic' lime; 'slightly energetic' lime; and 'inert' lime.[11] Vicat wrote five major treatises dealing with mortars, and his extensive experiments established one fact concerning hydraulic limes: no limestones are able to produce a hydraulic lime, unless silica is present in combination with alumina.[12] Other treatises which followed Vicat's never totally disputed this fact. A few altered it, but most agreed with his results.

Collet Descotils was one scientist who worked independently from Vicat, though during the same years. He devoted considerable time to the examination of limes and their clay content, trying to shed further light on Smeaton's clay theory. In 1813 Descotils analyzed marl from Senonches and found that it contained nearly one fourth of silica. This led him to believe that silica was the sole source in a lime to impart hydraulic qualities. Even after Vicat published his test results a few years later, in 1818, and concluded that silica and alumina impart hydraulicity, Descotils still believed his tests were correct. Vicat stated that Descotils was not incorrect, just incomplete, in his opinions, as clay generally contains more silica than alumina. Oddly enough, Descotils ran some additional tests on silica, using sand rather than clay. His results showed that the silica did not assist in rendering the lime hydraulic, but that the two components did unite with each other. Despite the fact that silica proved hydraulic in clay, but not in sand, Descotils did not conclude that something else in the clay, namely alumina, could be acting with the silica to yield a hydraulic lime. He held firm in his beliefs, and only after Vicat ran extensive tests was his theory on silica proven incorrect—or, rather, incomplete.[13]

Many of the followers of Vicat and his work conducted tests on their own in an effort to enlarge on or further substantiate Vicat's silica and alumina theory. One follower, Johann F. John, prepared a variety of mortar mixes using pounded oystershells as the lime source. To the lime he added sand, clay, or manganese oxide. The purpose of his tests was to determine which components made a good hydraulic lime, while at the same time checking Descotils's theory on silica in clay and sand, and Bergmann's on manganese. His results substantiated Vicat's theory. The mortars made of the above ingredients all failed, with the exception of the oystershell and clay. In 1819 John published these conclusions in his treatise, Ueber Kalk und Mortel. While not delving into the clay theory in any depth, John did follow the same lines that Vicat was undertaking.

Other men continued to search for other ingredients in lime which might produce hydraulic properties. In the early 1830s M.P. Berthier studied the element magnesia. He analyzed a lime obtained from a mixture of limestone from Villefranche, near Paris, and silica, and found high levels of magnesia: 23%. Upon making this lime into a mortar, he noted that it yielded an energetic hydraulic sample. From this one lime sample, it could not be determined whether the magnesia acted alone in producing hydraulic qualities, or whether the silica aided it in yielding these properties. In 1832 Berthier, in a paper in the Journal des Mines, concluded that magnesia alone had no more effect than alumina in rendering a lime hydraulic. His tests had finally ruled out magnesia as a hydraulic source.

Several men—Vicat, M. Parandier, and M. Dumas—began their own test on magnesia to determine what reactions it created. Vicat analyzed two limestones and found them to contain 53.5% and 42.5% magnesia. At first his tests seemed to coincide with Berthier's. On the other hand, Dumas's tests brought him to the conclusion that if more than 10% of magnesia was present, the lime began to become poor. If more than 25% was present, the lime was classified "decidedly poor." Parandier also ran tests, and his results caused him to side with Berthier and Vicat.

For nearly six years the magnesia issue remained unsolved. Vicat's continual testing, however, finally brought him conclusive results on magnesia. In about 1837 Vicat submitted a paper to the Royal Academy of Sciences in Paris. The topic was the effect magnesia had in rendering certain limestones hydraulic. The paper attempted to correct the opinion given by Berthier in 1832. Vicat stated that he had produced hydraulic properties from magnesia, but that further testing was necessary. He stressed that the proportions of magnesia should be from 30 to 40 for every 40 of pure anhydrous lime. The stones Berthier had analyzed had only contained from 20 to 26 of magnesia for every 78 to 60 of lime. Vicat thought that the lack of proper proportions caused Berthier's negative results.[14] This 1837 paper of Vicat's also established Dumas's results as incorrect.

The period from 1756 until approximately 1855 was a time of intense research and testing in an effort to achieve a good hydraulic mortar for the building industry. Many men spent countless hours proving, disproving, or creating new theories on what made a lime hydraulic. Vicat was clearly the leader in this field, with the groundwork laid by Smeaton. Vicat's work has remained largely undisputed. The knowledge that these and other men brought to light in their treatises probably enabled men like Parker and Aspdin to devise harder mortars, namely Roman and Portland cements. These latter inventions drove men back to their laboratories in a continuing effort to create better cement.

Artificial Hydraulic Limes

For centuries pozzolana had been known as the ingredient in mortar to enable it to set and maintain its hardness under water. Vitruvius had spoken of it; Smeaton used it on the Eddystone lighthouse. However, pozzolana was not as abundantly found in northwestern Europe as it was in Italy, or as trass was in the Rhineland. Importation costs often prohibited its use. Therefore, men sought alternatives. Guyton de Morveau is credited with being the first to add man-made ingredients to lime to achieve hydraulic properties.[15] One of his first (circa 1774) recipes, artificial meagre lime, called for 45 parts of pulverized common lime, 2 parts of clay and 3 parts of black manganese oxide.[16] He attributed the hydraulic qualities to the addition of the manganese.

Smeaton also touched on the subject of artificial hydraulic limes. He showed that, by adding minion or calcined iron ore, a mortar as hydraulic as that containing pozzolana could be made. His research was verified by Barthelemy-Faujas de St. Fond, and M. Daudin, in 1797 and 1808 respectively. Both men added iron bits or filings to lime and achieved hydraulic qualities. They believed, like Smeaton, that it was the iron, whether found in nature or found in a smithy, that gave a mortar the quality of hardness.

Throughout this period of testing and development of various theories, some men chose to retain the ideas set down by Vitruvius and Pliny. While the Romans worked mainly with pozzolana found naturally in their country, it is known that they also used some artificial pozzolanas. Brick dust, tile dust, or powdered pottery produced an impervious mortar. Belidor, already shown to be an avid follower of Vitruvius, recommended, as substitutes, stone chips and scales from a blacksmith's forge, to his readers in 1737 when he published _Architecture Hydraulic_. Furthermore, he suggested as one useful recipe a mix of 12:6:9 pozzolana:sand:quicklime with 13 parts of broken stone and 3 parts of powdered slag or forge cinders added for extra hardness. M. Raffineau de Lille was another scientist who suggested and preferred pounded brick.

While men such as Raffineau de Lille thought they were following the work of the ancients, they unknowningly were promoting new theories! Vicat ran many experiments on clay, some of which included pounded brick. He showed that this material, burnt clay, was a better additive to lime mortar than was trass. Burnt clay was closer in composition to pozzolana than was trass. Vicat's recommendation for the use of burnt clay or pounded brick was later supported by John.

Men's opinions remained divided over which artificial additives could produce a hydraulic lime. As shown, some men preferred the Roman ways; others preferred natural pozzolanas, such as trass; and still others strove to achieve new technological advancements in this field. In Holland, trass was an important additive to building mortar. In France, however, in 1782 - 83, one engineer, Jean R. Perronet, chose to use the Roman-suggested tile dust. Most mortar for the Bridge of Neuilly was composed of 1 part of Vernon lime and 3 parts of sharp, clean sand from the Seine. The foundations exposed to water, however, were made with 1 part of Vernon lime to 2 parts of artificial pozzolana. This pozzolana was from tiles obtained from the tile works at Neuilly.

While the upper portion of this bridge was not exposed to water, except in the form of mist and rain, it nevertheless led some scientists to give thought to the rôle sand played in forming a hydraulic lime. Vitruvius had suggested the use of fossiciae, which had later been shown to be successful because of its alumina content. M. Wolfuis believed that dry, sharp sand was a necessary additive to create a hydraulic lime. M. Worledge conducted experiments that showed that dryness and sharpness were not as important as the size of the sand grains. He concluded that fine sand produced a weak mortar, while that made with larger grains was stronger. Disputes continued for some time.

In 1830-38 Major-General Sir Charles W. Pasley conducted many experiments on countless artificial additives for hydraulic mortar. His additives included pounded chalk, pounded flint, pure alumina, iron scales from an anchorsmith, and various metallic oxides and carbonates. Chalk was separately combined with tile dust, slate dust and Fuller's Earth from Reigate, but none of these mortars hardened under water. At first, the results led him to believe that many of these additives, praised by other men, were inadequate. Upon conducting the same test using another chalk, however, good hydraulic mortars were obtained. Pasley found that the additives he used were not sufficient by themselves to create a hydraulic mortar: the lime was equally important. Unlike Belidor, back in 1729, who had generalized his results from testing one or two clays to all clays, Pasley showed that results depended on the type of any one ingredient used. The original chalk he used was of too poor a quality to allow even good artificial pozzolanas to work. Retesting, using different chalks, brought better results.

M. Fred. Kuhlmann was another scientist who devoted a great deal of time to trying to improve the hydraulic qualities of lime. In 1841 he issued a patent based on his own research. This patent claimed that hydraulic properties could be conferred upon limes by calcining 100 parts of lime with 10 - 12 parts of alkali silicates. By 1855 Kuhlmann's work led him to conclude that hardening could be greatly improved by adding the silicate of soda or potash.

As technology advanced, and more men published their treatises, experimentation continued. Men continued to research the hypothesis that clay in lime was the cause of hydraulicity, while others moved into new areas of research and began to delve into artificial means of making lime hydraulic. Finally, there were those who so firmly believed in the facts set down by the Romans that they spent their efforts attempting to substantiate and reconfirm those facts. The overall outcome, however, was positive. Building mortars were developed to cope with a variety of situations, and men like Vicat made it possible to know which ingredients would produce the desired effects.

Other Controversies

The preparation of lime prior to making it into a mortar was as important as achieving desired effects, such as hydraulicity. Antione J. Loriot was one who believed that the method of slaking determined the hydraulic qualities. Furthermore, he believed that he had rediscovered the old Roman process of slaking. He stated, in 1765, that quicklime powder added to a thin lime:sand mortar just prior to use helped the mortar acquire increased strength and impermeability. The manner in which quicklime mortars cured soon proved Loriot wrong. He had based his theory on the misconception that the induration of mortars was the mere result of rapid desiccation, and thought it possible to obtain this by the introduction of a powerful absorbant.

Loriot's work proved not to be based on the old Roman method, and led some men to retain the Roman law spoken of by Pliny. Builders in ancient Roman slaked rich limes by immersing them in water, thus maintaining their plastic state until they were needed in a mortar. As they achieved good results with this method, it was written into law: it was forbidden to use lime which had not been slaked for three years.[17] De la Faye and St. Fond ran tests based on Loriot's conclusions and the methods set down by the Romans. They both sided with the Romans and believed that egg-sized lumps of lime should be immersed in water and allowed to slake thoroughly. The storage of lime for three years was not as important, they felt, as the lime's total immersion in water.

Smeaton and Vicat agreed with de la Faye and St. Fond. Smeaton, a contemporary of the latter two men, had slaked the lime destined for use in the Eddystone lighthouse, and then transported it across the country to the site in closed casks. His method appeared to follow that established by the Romans. As Smeaton conducted many tests on mortars and how they could be improved, he probably would have run experiments on better methods of slaking if he had thought the Roman process inadequate. As he did not, it can be assumed that to him the ancient way of slaking was satisfactory.

The system that Smeaton employed was precisely the one recommended by Vicat almost 60 years later. However, Vicat confined this method to rich limes only. For hydraulic or slow slaking limes, he suggested that the limes be reduced to a powder and partially slaked before using them in a mortar. His theory behind this method was that a sudden immersion would rob the hydraulic lime of its carbonic acid, and consequently its ability to harden over a long period. M. Hassenfraz ran tests of his own on slaking and came to the same conclusions as had Vicat.

In 1829 Treussart conducted similar experiments and obtained results that later led Vicat, and others of his opinion to be proven wrong. From the beginning of his tests Treussart believed that the saturation of lime with water, followed by storage in closed casks, was injurous to the lime and the qualities it imparted to the mortar. He agreed that the lime should be slaked, but argued that once slaked it should be used immediately while still fresh. He found that during prolonged slaking too much carbon dioxide was absorbed. This process, he thought, should begin with slaking, but finish in the mortar where carbon dioxide in the atmosphere had replaced the gas in the lime. As this gas was absorbed into the lime it strengthened it. If the absorption took place entirely during the slaking process and subsequent storage, then the lime, Treussart believed, lost much of its concretionary force once it was finally ready to be used in a mortar. Subsequent research and experience proved Treussart right.

Analyses

While experiments on various mortar mixes or components for mortar were being conducted, some scientists began analyzing different limestones and pozzolanas. Their aim was to try to find some correlation between their findings and those obtained from the experiments. Vicat's tests, for example, dealt mainly with balls of mortars, as had Smeaton's. They determined that it was the clay, or silica and alumina, that gave a mortar strength. Men like Bergmann, Vitalis, and Berthier, however, began at the source, the limestone or pozzolana, and began testing it to see if the hardening and strength qualities were acquired from ingredients in the source itself, or from its interaction with other ingredients in a mortar.

Table 2 lists some of the many sources analyzed. It shows how high the percentages of some of the ingredients were, which caused men like Vicat to believe that silica and alumina were sources of strength. A similar conclusion can be reached concerning iron oxide. The large quantities given may perhaps explain and substantiate Smeaton's belief

TABLE 2: This table gives the percentages of the elements in the limestones and other materials listed in Graph I. Furthermore, a complete breakdown of each of the samples is given to enable the reader to clearly see which ingredients carry high percentages.

Sample No.	Name	Analyzer (Source)	Lime	Silica	Alumina	Iron Oxide	Magnesia	Soda	Potash	CO_2	water	other	manganese	alkalies
	Blue Lias lime, Monmouthshire	(Spackman)	83.4	7.3	2.3	1.5	3.6	0.3	0.6			0.8		
	Blue Lias lime, Leicestershire	(Spackman)	57.4	21.1	5.1	9	0.6	0.4	0.9			5.6		
A	Lena limestone	Bergmann	90	6			4							
B	Rouen hydraulic limestone	Vitalis	68	6	12	2					12			
C	Calcined Siliceous iron ore	Daudin		50	16		3							
D	Portland cement	Vicat	65.3	19.8	10	0.8						4		
E	Artificial hydraulic lime	Berthier	51.9	15	3.4		3.4				28.3[a]	1.4		
F	Roman cement	(Spackman)	45.1	15.4	5.6	6.8	0.8			25.7			0.5	
G	English cement-stone	Berthier	65.7	13	6.6	6	0.5				1.2			
H	Boulogne stone	Berthier	61.6	15	4.3	9					6.6			
I	Italian pozzolana	Berthier	8.8	44.5	15	12[b]	4.7	4.1	1.4		9.2			
J	Tufa stone from trass	Berthier	2.6	57	16	5[b]	1	1	7		9.6			
K	Oystershell lime	(Eckel)	85.5	6.3	0.4	0.3	0.3			0.7	4	0.6		0.8
L	Sheppy stone	Berthier	69	18	6.6	3.7	0.2				1.3			
M	Arenes	Vicat	trace	42.1	23.6	22.5								1.3

TABLE 2 cont.

Sample No.	Name	Analyzer (Source)	Lime	Silica	Alumina	Iron Oxide	Magnesia	Soda	Potash	CO_2	water	other	alkalies
N	Hydraulic lime- stone	(Eckel)	47.5	12.4	0.6	0.5				37.3			
O	Marl	(Eckel)	51.2	1.2	0.5	0.4	0.4			40.6		0.3	5.8
P	Normal clay	(Eckel)	1.6	63.5	24[c]		1			2.5	7		0.8
Q	Limey clay	(Eckel)	14	46.8	19.2[c]		3.6			15.8		1.2	3
R	Vesuvius pozz- olana	(Eckel)	9	44.5	15.8	16.3	trace				3.5		11
S	French pozzolana	(Eckel)	8.2	47.9	34.2[c]		3.9				3.2		2.6
T	Vassy cement	(Spackman)	46.8	16	6.5	3.6	1.5			20.6			

[a] Water and CO_2 are combined in this figure

[b] Iron oxide and titanium are combined in this figure

[c] Alumina and iron oxide are combined in this figure

that iron played an important role in producing hydraulicity.

A comparative study can be made between the sources listed and the analyses for Blue Lias lime. This latter limestone was known to be naturally hydraulic; similar findings can be seen in many of the other sources analyzed. The percentage figures for silica, alumina, and magnesia from Table 2 have been graphically compared (Graph 1) with the Blue Lias equivalents to show further how these elements can be sources for hydraulicity. Naturally, the pure clays and pozzolanas have percentages higher than even the Blue Lias figures. On the other hand, it can be expected that a material such as oystershell lime would have percentages much lower than those for the Blue Lias limes.

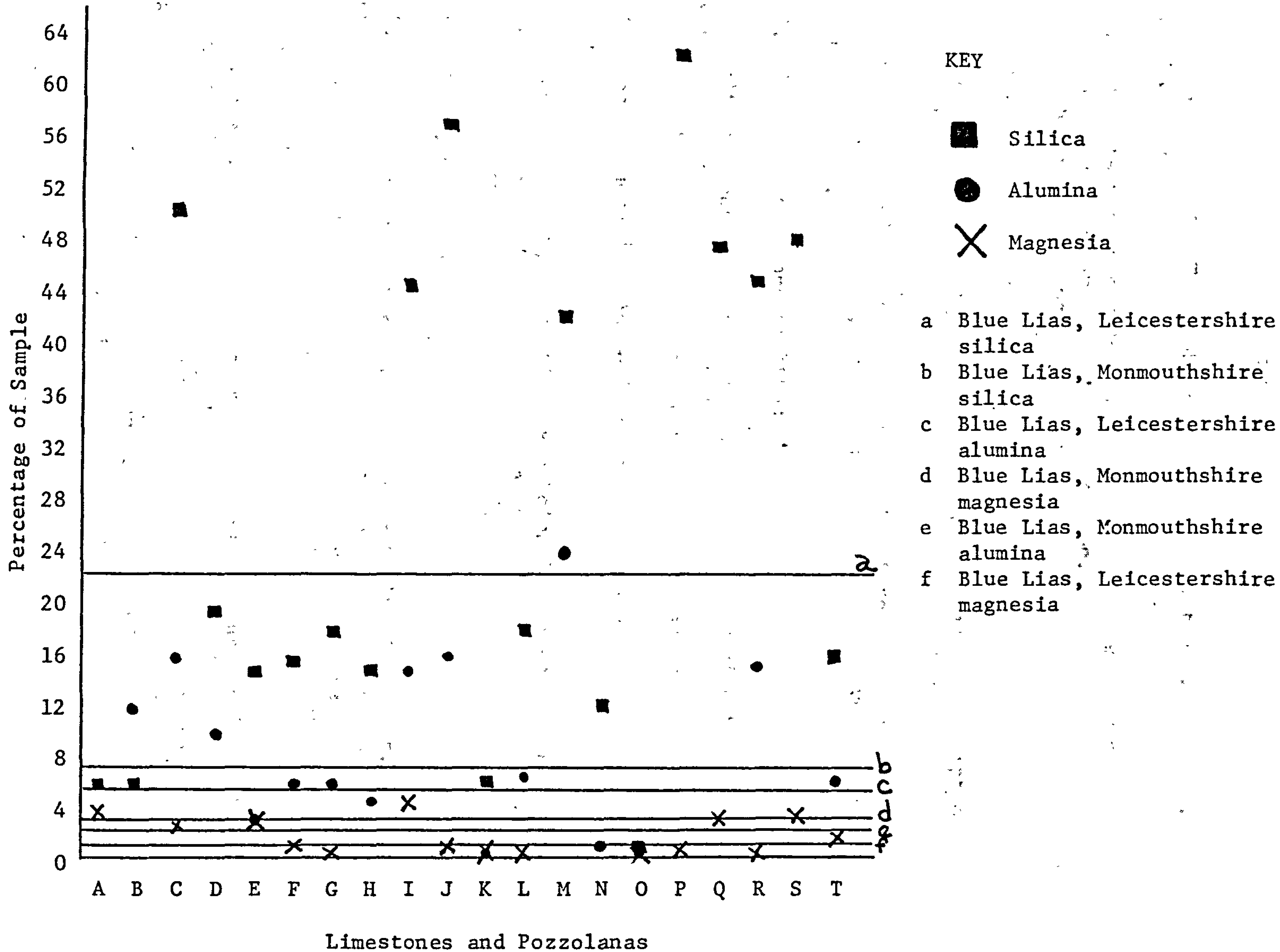
Conclusion

For one century, beginning in 1756, the issue of obtaining a strong, durable mortar was of great concern to many scientists. Theories, such as strong lime being produced only from hard, white limestone, set down centuries before were questioned as to their validity. Smeaton was the first to disprove substantially these 'rules' through his experiments on lime. Vicat followed with more experiments in 1818, resulting in linking hydraulicity to clay or silica and alumina found in certain limestones.

The quality of mortars was also considered to depend on the additives employed and the storage of all ingredients as well as the chemistry of the lime. Extensive experimenting was done throughout the century, 1756 - 1855, finally ending with a greater understanding of building mortars, particularly lime mortars.

The outcome of all these disputes had its effect on the building industry as additional mortars and cements were devised. Natural and Portland cements were developed, beginning in 1796, bringing further discussions and tests. And the concepts behind strong, durable mortars were under discussion all over again.

Graph 1: A Comparative Study of silica, alumina, and magnesia found in Blue Lias lime and various other limestones and pozzolanas.



References and Notes

1. Vitruvius, The Ten Books on Architecture, trans. Morris H. Morgan (New York: Dover Publications, Inc., 1960), p. 45.

2. No tests were conducted to prove that different limes, chalks and clays produced the same qualities in a lime. The clay Belidor tested probably was poor, and he incorrectly applied his conclusions to all clays. His experiments could well have thrown anyone off the track towards attributing clay as the source of strength for lime.

3. John Smeaton, A Narrative of the Building and A Description of the Construction of the Eddystone Lighthouse with Stone (London: Longman, Hurst, Rees, Orme, & Brown, 1813).
Despite this work being published for the first time in 1791 (a year before Smeaton's death), the tests and observations were made in approximately 1756.

4. Smeaton, Eddystone Lighthouse, 108.

5. Although Smeaton's process involved adding minion to lime, thus classifying it as an artificial hydraulic lime, his theory on this subject led other men to discover ferruginous substances within a lime.

6. See Footnote #2. As Belidor may have misled scientists, so did Smeaton.

7. Louis J. Vicat, A Practical and Scientific Treatise on Calcareous Mortars and Cements, Artificial and Natural (London: John Weale, Architectural Library, 1837), p. 163.

8. Vicat, Calcareous Mortars, 183.

9. To doublecheck his work, Vicat ran some tests on iron. He only succeeded in further disproving Smeaton's iron oxide theory and concluded that hydraulic limes, especially those which are strongly colored by iron, cannot, by mere union with water, form anything but bodies which are light and of moderate hardness.

10. Louis J. Vicat, Recherches Experimentales sur les Chaux de Construction, les Betons et les Mortiers Ordinaires, 1828.
Excerpts from this treatise are quoted in Charles Spackman, Some Writers on Lime and Cement From Cato to Present Time (Cambridge: W. Heffer & Sons Ltd., 1929), and George R. Burnell, Rudimentary Treatise on Limes, Cements, Mortars, Concretes, Mastics, Plastering, etc. (London: John Weale, 1850).

11. Vicat, Recherches Experimentales.

12. Vicat, Calcareous Mortars.

13. Vicat, 151-2.

14. Vicat, 150.

15. Some documents, namely Spackman, Some Writers, 11, credit M. Bagge in 1778 with discovering artificial pozzolanas. He found that hard black shale from Wesneborg in Sweden was a suitable replacement for pozzolana from Naples.

16. Here, manganese and clay are added to the lime to produce hydraulic qualities. In 1779, it had been shown how Bergmann used the manganese with a limestone to achieve a naturally hydraulic lime.

17. John Bostock and H.T. Riley, The Natural History of Pliny (London: Henry G. Bohn, 1855).

Excerpts referencing the Roman law are quoted in Burnell, Rudimentary Treatise, 46.

Chapter 2: The Development and Manufacture of Cement

Introduction

With the advent of James Parker's Roman cement in 1796, the stage was set for another series of disputes similar to those concerning lime. For the next century (1796 - 1904), until the introduction of British standards and the amalgamation of the cement industry, scientists were constantly seeking new manufacturing techniques to better their product as well as promote sales. One man, I.C. Johnson, even went so far as to chemically analyze a competitor's cement in an effort, some authors say, to 'steal' the product for his employers.[1]

Materials and production methods were key issues written about in treatises and government reports, and encompassed both natural and artificial cements. The nineteenth and early twentieth centuries were considered a competitive period. First natural cements reached the market, each inventor claiming his superior, beginning in 1810 when Parker's patent expired. Then in 1824 Joseph Aspdin introduced Portland cement, an artificial cement. By the 1860s and 70s the artificial nature of these cements proved to cause the demise of the natural cement industry. This was attributed to the fact that being artificially produced, the former's properties could be better regulated. As history has shown, artificial cements have further increased in popularity since, bringing about the introduction of such specialized Portland cements as Rapid-hardening and Low-heat cements.[2]

The main topics for discussion concerning cements were: 1) the septaria origin and its effect on the end product; 2) the importance of vitrification; 3) the type of kiln used and its effect on the quality of the cement; and 4) the wet vs. the dry process in manufacturing. Time, experimentation, and technology eventually shed light on these important issues, but for over 100 years they were heatedly debated.

Septaria Origins

When Roman cement and other natural cements were first introduced, chemical analyses of the ingredients had not yet been widely published and circulated.[3] Smeaton's work, though finished, was not readily available, despite the publication of Eddystone Lighthouse in 1791, and Vicat's work would not be known until 1818 at the earliest.[4] Natural cements, nevertheless, gained popularity in Great Britain due to the ease with which they were manufactured and the quick-setting properties they brought to a project.

Parker established the natural cement market in England by merely picking up 'nodules of clay' on the northern seaside of the Isle of Sheppy and slaking them. Patenting his procedure in 1796 under 'Parker's Patent Cement,' he held the market for 14 years (sometimes calling his product "Roman cement"). Others, however, waited in the wings until the expiration date of the patent, 1810. In 1811 and shortly thereafter, the market was flooded with new, but similar cements. Each inventor/patentee claimed superiority based on the type of septaria used, but often won buyers by lowering the price.

Atkinson's Cement was made from shale beds of the Lias formation in Whitby, Yorkshire; Frost's Artificial Cement used chalk and mud from the Medway estuary.[5] Both were popular and typical of others like them on the market, but neither surpassed Parker's Roman cement, despite their lower prices.[6] Parker, for example, obtained most contracts from the government until the latter began their own manufacturing ot the cement.[7] One company, Francis & White, keen on overtaking Parker, even went so far as to make frequent visits to the Isle of Sheppy for the septaria, despite the questionable legal rights of picking up the stones.

The basis of producing a good natural cement was more fully understood when Vicat's book, Recherches experimentales sur les chaux de construction, les betons et les mortiers ordinaires, was published in 1818. The inferiority of a mortar mix stemmed from the clay and lime content. Vicat stated that when the proportion of clay in calcareous minerals exceeds 27 - 30%, up to 60%, they furnish a kind of natural cement.[8] Medway clay, for example, proved to be one of the better clays, according to Prince of Schonaich-Carolath in Tarnowitz, Poland, due to its contents of corundum, iron-oxydule, and alkali-silicates.[9] It is even known to mix easily with chalk. Unfortunately for Frost, though, when these two ingredients were combined, the degree of hardness was retarded, and thus Frost's Cement proved inferior for the times.[10] Roman cement was known for its "near 'flash' set," both in water and air, and for the "very considerable degree...of hardness" it reached within twenty minutes.[11] The lack of equality in this property and the fact that the ingredients were only partially mixed during manufacture led to Frost's Cement remaining an inferior product.

Atkinson's Cement similarly suffered from the inventor's choice of ingredients. Entering the market in 1811, this product remained available to the public, according to advertisements, until approximately 1870. The original choice of quarry sites was along the Whitby coastline, and this selection may have been based on the knowledge that the Lias formation produced excellent hydraulic limes and clays.[12] Lias shale, however, was known for its quantities of 'alum,' and this component had been attributed, in part, to the cause of such ensuing problems as cracking.

Natural disasters seemed to plague Kettleness, Whitby manufacturers of Atkinson's Cement almost from the beginning. On several occasions, just after the completion of new or remodelled cement works, cliff falls and landslips occurred which "so completely swallowed up [the factory] as not to leave a vestige behind them."[13] Some works were destroyed beyond repair. This extensively interrupted the production schedule and often limited the availability of Atkinson's Cement.

The popularity of Atkinson's Cement also suffered initially, due to its tendency to crack underwater. The cracking could be prevented by increasing the quantity of sand (about 3 parts of sand to 1 of cement), but only at the expense of strength. Roman cement proved better on this account, thus preventing Atkinson's Cement from ever becoming popular for underwater projects. The latter, therefore, became classified as a cement suitable for stuccoing, or for mouldings and ornaments. The church of St. Mary-le-Bow, London, was stuccoed with Atkinson's Cement in 1816 as were a number of London houses.[14]

Chemical analyses of Roman cement, Atkinson's Cement, and Frost's Cement are given in Table 3. According to Vicat's definition of natural cements, Medway mud far exceeds the percentage of clay contents to actually be termed 'natural.' Furthermore, Medway mud contains an extremely low content of calcium oxide, thus making it difficult to achieve a set in mortars. This, in part, hindered the success of Frost's Cement. Frost tried to correct this deficiency by adding chalk.

Atkinson's Cement and Frost's Cement were just two of the popular natural cements on the market. However, the septaria used, whether that made from ingredients or that found whole, proved to be unsuccessful in producing a natural cement that would take the market by storm as did Parker's Roman cement. Even the fact that Roman cement was the most expensive natural cement available did not increase sales for other manufacturers and inventors.

Vitrification

Roman cement was an alternative to hydraulic mortars. Parker believed that his cement, while manufactured by a process similar to that of hydraulic lime, was better due to the state of vitrification reached. Vitrification, in other words, was directly related to hydraulicity. He was the first to consider any correlation between the setting process and the temperature of the furnace at the firing stage. Thomas Telford picked up on this and conducted a series of tests to justify Parker's 'theory on burning.'[15]

In the first half of the nineteenth century, it generally was the practice to underburn cement or stop just short of vitrification.[16] Overburnt, or vitrified, cement was rejected in the belief that it had lost its setting properties.[17] Many of the inferior cements, such as Frost's Cement, followed this 'underburning' mode, but Parker believed that to achieve a superior cement the septaria must be burnt

	Roman Septaria	Medway Mud	Whitby Liassic Shale
CaO	54.00%	1.15%	17.78%
SiO_2	25.00%	60.66%	38.00%
Al_2O_3	9.00%	15.05%	14.85%
Fe_2O_3	8.00%	9.63%	4.75%
MgO	2.00%	1.79%	3.42%
Cementation Index	1.51	52.76	5.58
C.I. of Medway mud with chalk of CaO = 98.00%:		1.90	

Table 3: Analyses of Natural Cements

just sufficiently to commence vitrification.[18]

The septaria or nodules of clay were first broken into flakes about two inches in diameter by boys with hammers, then carried in baskets to kilns. The kilns were loaded with alternating one foot layers of fuel and septaria. For three days the firing remained undisturbed, after which burnt stone was removed from the bottom opening (and replaced through the top) every 24 hours. After burning, the stone was carried to a cement mill for grinding, sifting, and packing into airtight casks.[19] Parker insisted on grinding his cement to an impalpable powder as he believed the finely ground cement was of a higher strength.

Parker was so sure of his vitrification theory that he established an early form of quality control at Parker & Co. to insure clients of stable properties. He suggested removing a handful of cement from each cask prior to its use, gauging the cement with water, and timing its set. "If it hardens in about 20 mins it cannot be more indicative of durability. If it takes much longer to set it should be rejected as being either underburnt or imperfectly ground or both."[20] Telford's published test results backed this up.

There is no clear answer as to why Roman cement, burnt to near vitification, was successful, while competitors of the time produced inferior, underburnt cements. (Telford used the former product on a number of occasions and liked both its short- and long-term properties of set and hardness.[21]) William Aspdin, however, unknowingly helped answer this when he improved on his father's invention of 1824: Portland cement. In 1843 in The Builder, William advertised an improved Portland cement, one of increased strength.[22] Based on today's cement manufacturing techniques, it could only have been by clinkering or 'overburning' the raw ingredients that Aspdin achieved such an improvement. Aspdin had a limited knowledge of chemistry, so it can be assumed that, like Parker's Roman cement, Aspdin's discovery was purely accidental.

In time Aspdin's clinkering process was generally accepted, and all future Portland cements were based on the 'overburning' technique. As Roman cement was burnt to the point where vitrification commenced, it can now be understood why his product was popular: it was stronger due to the firing procedure, despite the prevailing idea that cements must be underburnt. It is interesting to note, however, that some men still held to the 'underburning' theory, regardless of evidence to the contrary. General Sir Charles Pasley, right up to the time of his death in 1861, never believed that clinkering was <u>essential</u> in making a true Portland cement.[23] Frederick Ransome, as late as 1885, was also unaware of the necessity for burning the raw ingredients at a temperature high enough for vitrification to commence.[24]

The studies conducted by Parker, Telford, Vicat, and others helped Edwin Eckel, in 1922, establish a hydraulic index and a cementation index whereby most cements and mortars could be classified based on their hydraulic "possibilities."[25] This can be used to further understand vitrification.

The hydraulic index was defined as the ratio between the percentage of silica plus alumina and the percentage of lime. The answer should then fit into one of the following classes:

Hydraulic Index	Product
Less than 0.10	Common limes, quicklimes
0.10 to 0.20	Feebly hydraulic limes
0.20 to 0.40	Eminently hydraulic limes
0.40 to 0.60	Portland cements
0.60 to 1.50	Natural cements
1.50 to 3.00	Weak natural cements
3.00	Pozzolanas[26]

Eckel listed several defects in this index, mainly that there was no allowance made for the action of either iron oxide or magnesia. As a result, he altered the index and renamed it the Cementation Index:

$$\text{C. I.} = \frac{(2.8 \times \%\text{silica}) + (1.1 \times \%\text{alumina}) + (0.7 \times \%\text{iron oxide})}{(\%\text{lime}) + (1.4 \times \%\text{magnesia})}$$

Cementation Index	Product
Less than 0.30	Common limes, quicklimes
0.30 to 0.70	Feebly hydraulic limes

0.70 to 1.10	Eminently hydraulic limes
1.00 to 1.15	Portland cements
1.05 to 1.15	Natural Portland cements
1.15 to 1.60	Natural cements
1.60 to 2.00	Weak natural cements
2.00 to 3.00	Very feeble natural cements
3.00	Pozzolanas[27]

The Cementation Index was linked to vitrification in that advance chemical analysis could determine whether a given rock would be suitable for a specific cement. It proved more accurate as the index remedied the faults linked with the Hydraulic Index. Basically, the key is that as the index rises, the temperature necessary for burning decreases and the hydraulic activity decreases.[28]

Referring back to Table 3, the Cementation Index was calculated. For Roman cement, the value is 1.51; and for Frost's and Atkinson's Cements, they are 1.90 and 5.58 respectively. This would indicate that Roman cement required a higher temperature, and in fact Parker's did indeed burn longer and higher. While Parker and other manufacturers of natural cements would not have had this index at their disposal, it does, today, aid in understanding the differing theories on optimal burning time. Based on the Index, vitrification was linked to hydraulicity.

Kilns

For both natural and artificial cements, the keen competition to produce a commercially successful cement was reflected in the type of kilns built as well as the ingredients chosen. During the eighteenth century, three different shapes of kilns were used: the bottle, the chamber, and the rotary kiln. There were several variations, for example, as many as seven on the basic "chamber kiln." Men learned from experience and strove to develop a kiln that would produce a high yield while keeping labor and fuel costs at a minimum.

In the early years of the cement industry, the traditional bottle or dome kiln was employed (Figure 1). Shaped like a circular bottle or inverted cone, it had been popular in the seventeenth century for the burning of limestone and was used, in the first decades of the 1800s, by Parker, Frost, Aspdin, and others. It was termed 'intermittent' due to the fact that once filled with coal or coke, it was fired at approximately 2000 - 2500^{o} F and left alone for up to six days, then interrupted for clinker removal and reloading.[29] The removed clinker was then conveyed to the grinding mills.

Productivity using the bottle kiln was limited. Labor and fuel were costly in the early 1800s, while the output was a mere 20 - 30 tons per week.[30] More important, however, was the quality of the product. It was not uncommon for large amounts of underburnt material to pass through with the clinker. Large chunks were removed and thrown back into the kiln, a costly procedure, but the remaining portion in the clinker occasionally affected resulting batches. Partly for this reason, Parker insisted that sifting and careful grinding, after burning, be a part of the manufacturing process and that his clients conduct his recommended standard test upon opening a cask of Roman cement.

Joseph Aspdin experienced similar problems during the early years of artificial cement production. He found that when unburnt portions of limestone existed in the clinker, it was harder to mix it with clay later. Therefore, the 'double-kilning' method was introduced.[31] Aspdin first calcined the limestone, then combined it with the clay and calcined the two together. A fine, thoroughly mixed cement was the result, and even when the cost of fuel was high, the double burning cost little more. This was Aspdin's solution to the faults of the bottle kiln.

The chamber kiln evolved around 1854 to eliminate waste and other problems experienced with the bottle kiln. For the first time, the heat from the waste gases was utilized, and chambers or flat roofs were introduced, above the firing chamber, to dry any slurried raw ingredients. This innovation tended to eliminate the need for separate drying areas and reduced fuel consumption dramatically.[32] Also, it

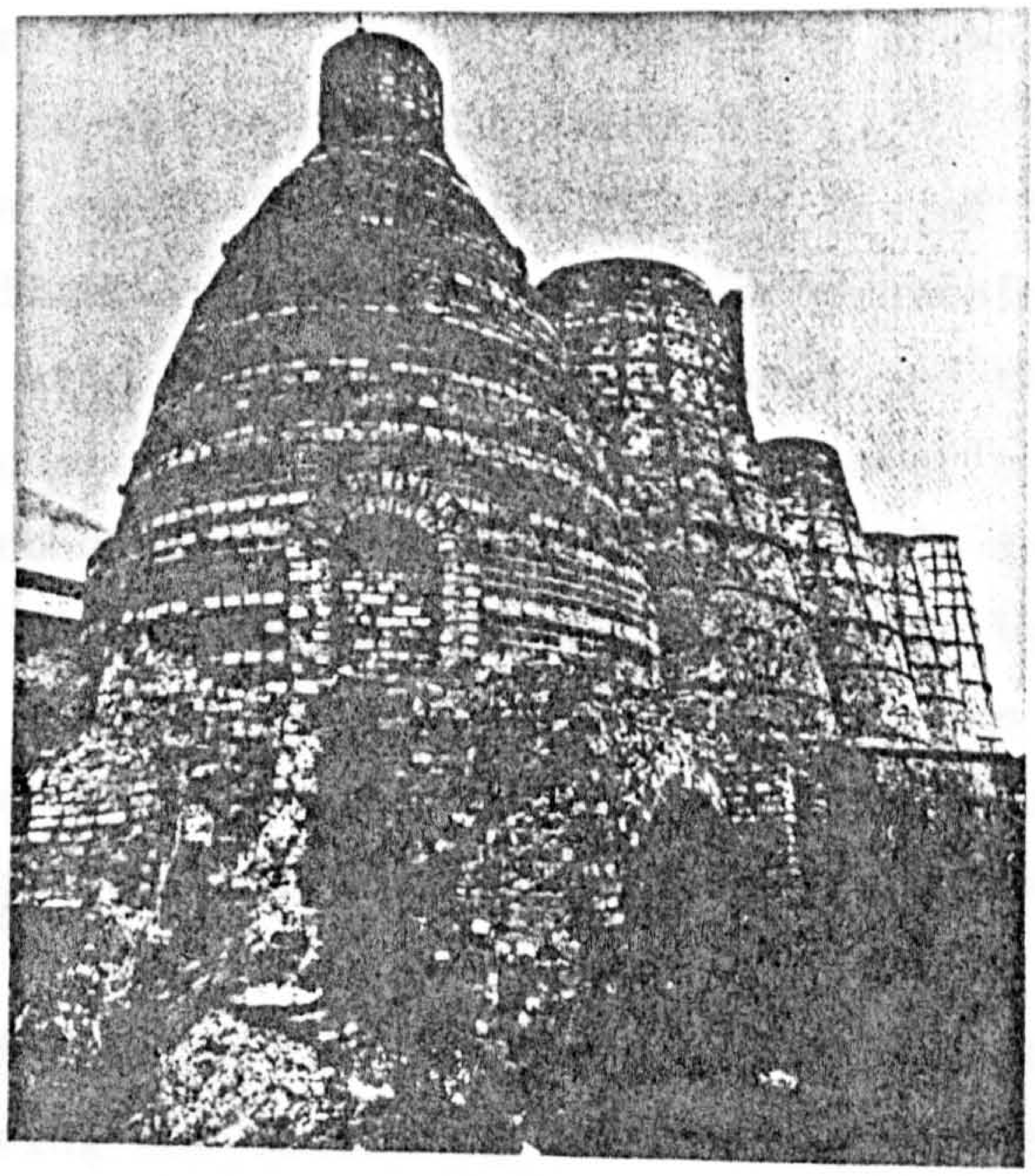
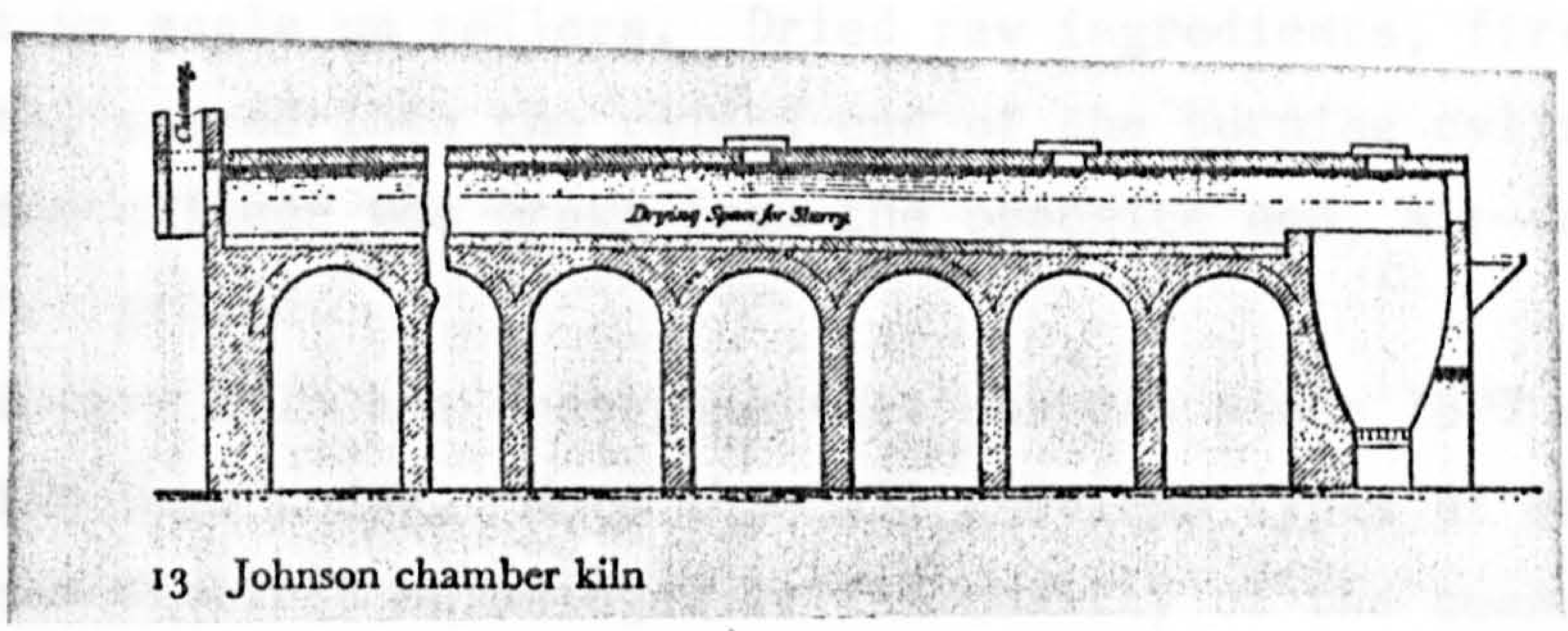


Figure 1: The Bottle Kiln

Taken from: A.J. Francis, The Cement Industry 1796-1914: A History (Newton Abbot, Eng.: David & Charles Publishers Ltd., 1977), 68.



13 Johnson chamber kiln

Figure 2: The Chamber Kiln

Taken from: Francis, The Cement Industry, 153.

was the first of many future kilns to be classified as 'continuous,' as opposed to 'intermittent.' The kilns could be drawn and reloaded without the need to extinguish the fires.

I.C. Johnson patented a popular kiln in May of 1872 (Figure 2). It consisted of an inverted bottle kiln with a horizontal chamber above. The draft of the kiln opened into this chamber and the chimney was placed at the opposite end. Inlets in the chamber's roof allowed slurry to be pumped in to a depth of 8 inches. Johnson's idea was that as the cement was being fired, the slurry was being dried by the released gases. When the clinker was removed, the slurry was merely raked into the kiln.[33] Variations on this theme were introduced and named after their inventors: the Batchelor kiln, the Hoffman kiln, the Schneider kiln.[34]

The main effects the chamber kilns had on cement were the uniformity in drying and calcining the raw ingredients more completely.[35] The more advanced continuous chamber kilns, such as Hoffman's, enabled burning to go on indefinitely as several kilns were incorporated into the plan. As one kiln cooled for drawing, another was fired, enabling some plants to draw a kiln per day.

The last kiln, the rotary kiln, revolutionized the cement industry. It was used as far back as 1853 in the alkali industry, but was first introduced to the cement manufacturers by Thomas Crampton in 1877. The patented kiln was a revolving iron cylinder lined with fire-bricks and mounted at an angle on rollers. Dried raw ingredients, first crushed by two rollers, passed into the raised end of the burning cylinder. After burning, the clinker was drawn from the opposite end, air-cooled, and then further ground.[36]

The rotary kiln has undergone vast changes since 1877 and is the primary kiln used today. More than all previous types of kilns, this one produced distinct advantages in the quality of the cement, stemming from the fact that the calcination process is totally controlled by the operator. The desired degree of burning could be regulated by altering the rotation speed of the cylinder, by increasing or decreasing the feed of raw ingredients, or by varying the force of the blast and the fuel quantity.[37]

Wet vs. Dry Methods

Once Portland cement became an accepted alternative to Roman cement, men began to use manufacturing methods which both saved time and improved the quality of the cement. Three methods resulted for reducing and mixing raw ingredients prior to firing: the wet method, the semi-wet (or semi-dry) method, and the dry method. Each had their drawbacks, but these were minimal; and with refining and careful regulation, these processes gained popularity and survived, along with the rotary kiln, to enter the twentieth century.

The wet method of Portland cement manufacturing was invented and developed in the United Kingdom for use by Thames and Medway manufacturers. It was designed mainly for such soft materials with high percentages of natural moisture as mud and chalk. The correct quantities of raw ingredients were placed in a circular vat, called a washmill, filled with water. A horizontally-revolving frame with a suspended harrow, fitted with steel tines, broke up any lumps and converted the mixture into a liquid containing from 32 - 42% of water. The fine slurry then passed through vertical gratings in the sides of the washmill into storage vats, pending drying and firing. Any stones present in the raw ingredients that did not break readily remained in the washmill and were removed from the bottom occasionally.[38]

The advantages of this method were two-fold. It enabled the soft materials to be reduced to a very fine slurry and permitted stones and flints, found in the Medway and Thames chalk, to be easily removed. A strong cement was ultimately produced when the raw materials were ground to a very fine state, and this could only occur by removing large extraneous materials. The wet method not only accomplished this, but did so in an economical fashion.[39] The two drawbacks to this method, however, were the risk of disturbing the fine combination of the slurry by irregular separation of water and the fact that the ingredients, having different specific weights, might not mix uniformly and thoroughly.[40]

The semi-wet (or semi-dry) method, patented around 1880 by William Goreham, was merely a shortened version of the wet method and later called the 'thick slurry process.'[41] The slurry was made as described above, but the water quantity was reduced to achieve a semi-plastic state before the slurry passed through horizontal millstones and directly on to drying floors. Books and periodicals, in describing the three methods, give very little mention, if any, to this particular method, leading one to believe it never became very popular.[42] This was verified by the fact that Goreham's process failed to accomplish accurate blending of the raw materials, but the fact that the slurry went directly into the drying chambers did reduce the risk of separation by gravity.[43]

While the wet process was more popular in Great Britain, the dry method was more extensively employed in other countries, particularly the United States. As an alternative to the wet method, it proved advantageous where raw, non-absorbent materials could not be sufficiently reduced by washmills. The shale or clay was first dried on heated floors; this was not considered necessary for the limestone. All the ingredients were then roughly combined in their correct proportions and ground and mixed by crushers or rollers, which reduced the products to approximately 1-1/2 inch lumps. These were then stored or sent to revolving drying chambers. Aspdin's 'double-kilning' process is considered to be an early form of this process.[44]

The main advantage to the dry process was that it did not entail as extensive a procedure as the wet method. Extra care was required, though, to ensure a thorough mixing of the ingredients. As both the wet and the dry processes break down the cohesion between the particles and leave the material in a finely divided state, the material itself determined which method was best (Figure 3).[45]

The developments made in the Portland cement industry in the latter half of the nineteenth century have been improved, but retained to this day. The extensive studies and tests, from which these three grinding and mixing methods were derived, show that Portland cement had become an extremely important product to the building industry. Some methods, such as the semi-wet process, never became popular and some of the disadvantages of the other two methods were overcome in time.

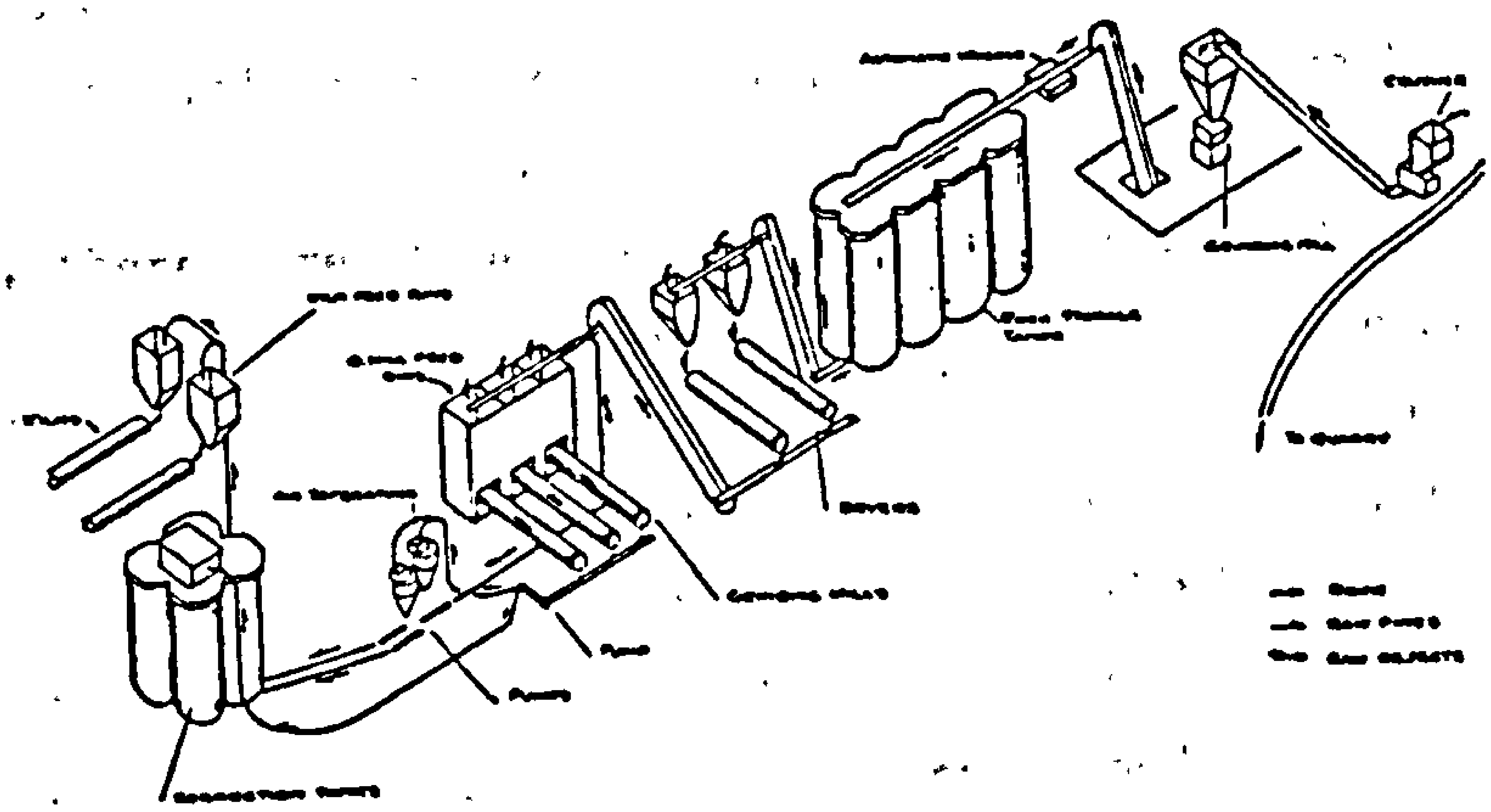


Fig. 20.—Dry Process.

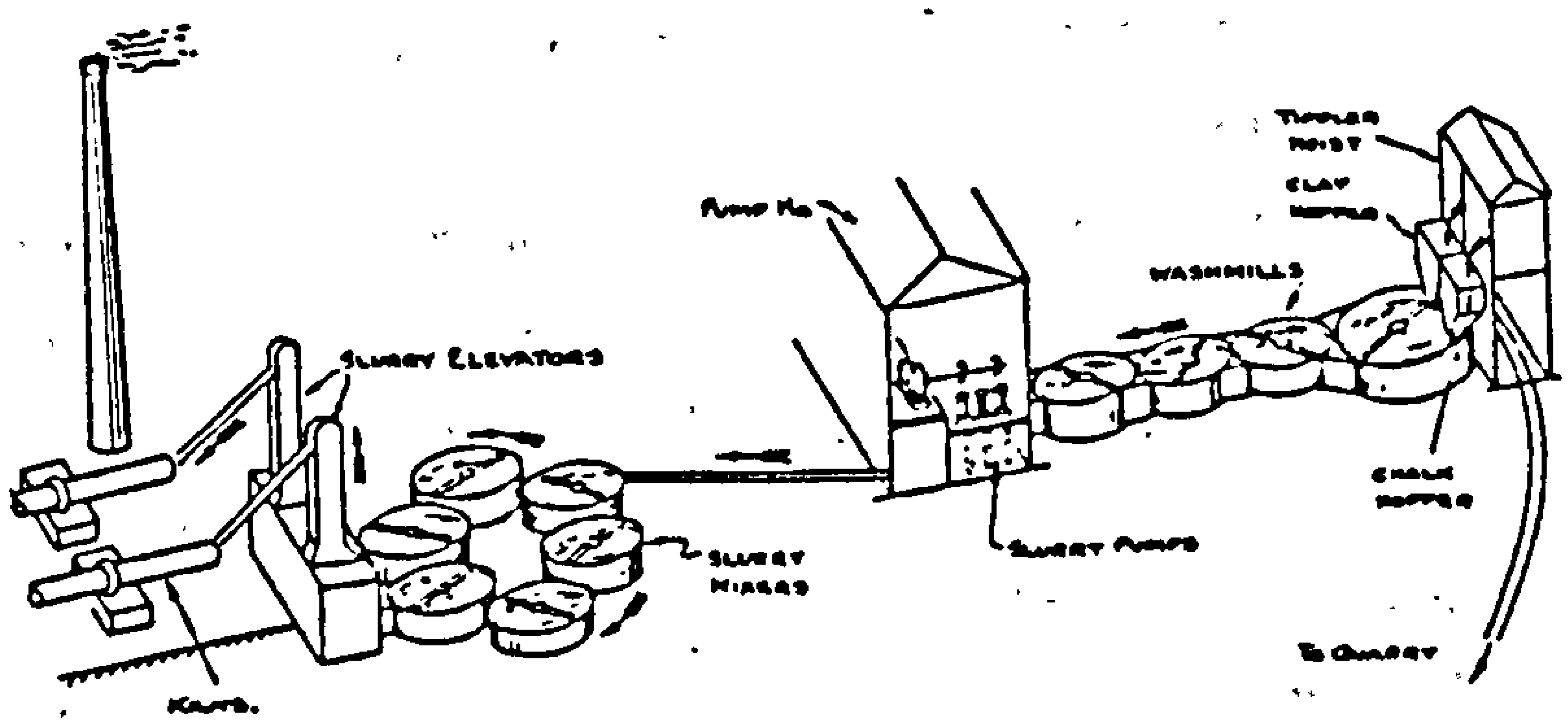


Fig. 21.—Wet Process.

Figure-3: The Wet & Dry Processes of Cement Manufacturing

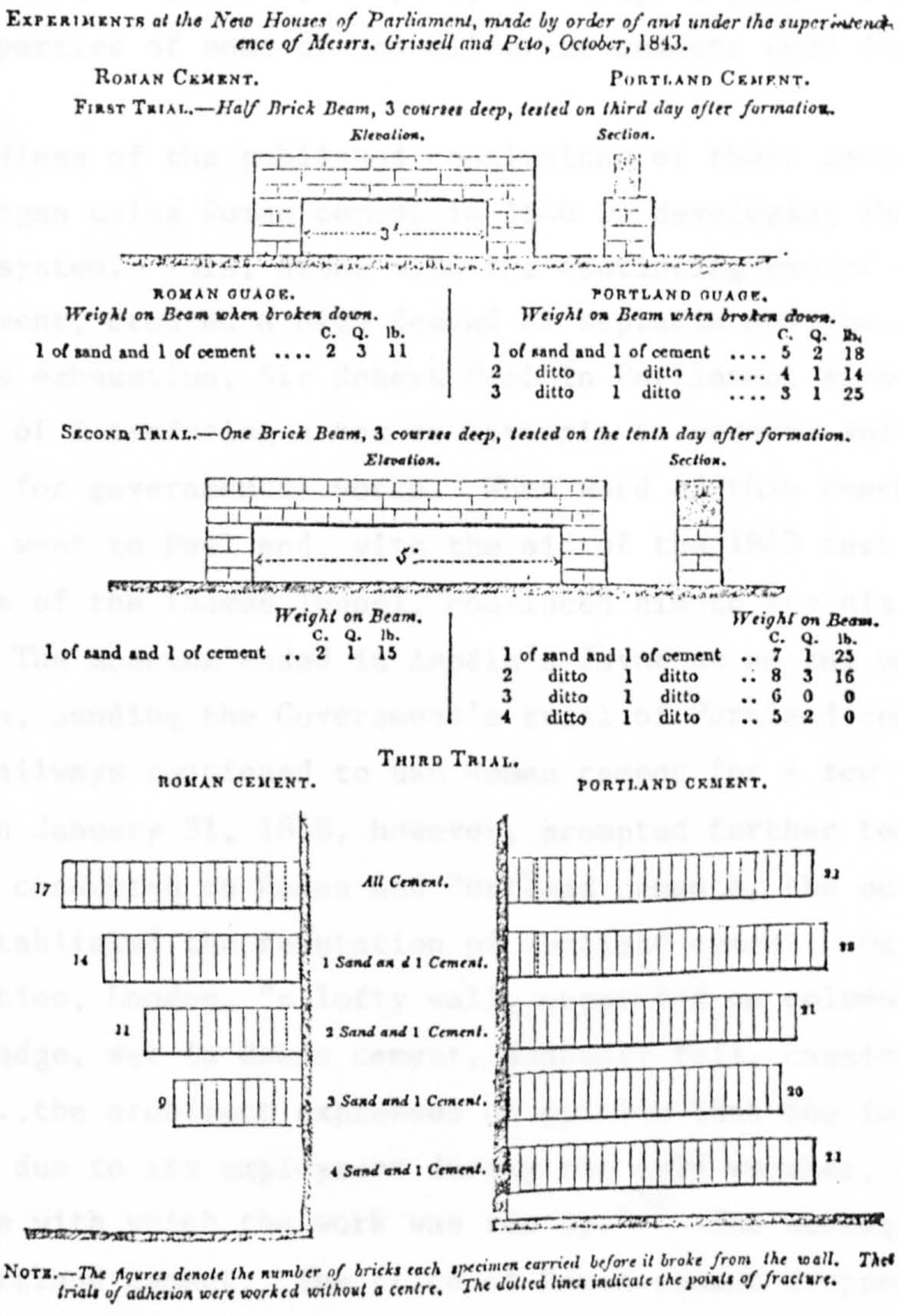
Taken from: A.C. Davis, Portland Cement (London: Concrete Publications Ltd., 1934), 73.

Portland Cement's Success

Roman cement was not easily superseded. It, and others like it, had proven themselves over the years, and with the lack of enforced specifications of standards concerning composition, setting time, and strength for Portland cement, the natural cements provided keen competition.

However, there were those who were willing to give Portland cement a chance, regardless of its newness on the market. Work began in 1825 on the world's first tunnel under a navigable river. Sir Marc Isambard Brunel, the designer, insisted, based on preliminary tests, that only Roman cement would do the job. The directors of the Thames Tunnel Company did not care as long as it was the cheapest Roman cement on the market.[46] In 1828, however, the tunnel became flooded and the directors insisted that a Portland cement be used to seal the damage. The Builder, in an 1844 article, stated that Wakefield cement, so named because one of Aspdin's plants was located there, was used.[47] The Portland cement cost Brunel 20 - 22 shillings per cask, exclusive of carriage to London, while Roman cement was running 12 shillings per cask, inclusive of shipping. The Builder went on to say that Brunel justified its use simply on that fact that "its merits required no other recommendation than an impartial trial."[48] Aspdin and other Portland cement manufacturers played on this, and eventually tried to claim credit for the success of the tunnel project. The tunnel survives today and has undergone only minimal repairs since its erection.

The cement issues raised by the Thames Tunnel project finally prompted some extensive experiments to be run on Roman cement and Portland cement at the New Houses of Parliament in 1843. Conducted by contractors Grissell & Peto, the tests included the construction of cantilevered beams and beams supported on both ends (Figure 4). Each beam was constructed entirely with Roman cement or Portland cement, using identical bricks and mix ratios, and after three days, loaded to destruction. The results of all the tests proved Portland cement to be considerably stronger. In a later reanalysis it was found that Aspdin's cement was 1.8 times stronger than the best Roman cement.[49] This



10 Results of the first official tests of Aspdin's Portland cement

Figure 4: Results of Grissell & Peto's tests

Taken from: A.J. Francis, The Cement Industry 1796-1914: A History (Newton Abbot, Eng.: David & Charles Publishers Ltd., 1977), 114.

was the beginning of a series of tests conducted on Portland cements, the most elaborate carried out by John Grant between 1860 - 1867. Grant's test reports were considered to be the earliest form of standard specifications.[50] Table 4, Graph 2, and Graph 3 give a comparison of the properties of some of the different cements used during these decades.

Regardless of the published conclusions of these tests, the British railways began using Roman cement in 1846 in developing their rapidly expanding system. This, along with the continuing use of the product by the Government, created a high demand on septaria and the price soared. Fearing its exhaustion, Sir Robert Peel in Parliament announced his intentions of introducing a tax on septaria to reserve sufficient quantities for governmental works. When word of this reached William Aspdin, he went to Peel and, with the aid of the 1843 test results and the success of the Thames Tunnel, convinced him to try his Portland cement.[51] The meeting ended in Aspdin's favor as no tax was placed on septaria, pending the Government's trial of Portland cement.

The railways continued to use Roman cement for a few years. An accident on January 31, 1848, however, prompted further testing. The tests were conducted on Roman and Portland cements, the outcome of which finally established the reputation of Portland cement. On that date at Euston Station, London, "a lofty wall, supported on columns formed of bricks on edge, set in Roman cement, suddenly fell, causing the death of 2 workmen...the architect expressed an opinion that the failure of the cement was due to its employment during the cold weather, and to the great haste with which the work was run up."[52] The subsequent tests favored Portland cement. The price of Roman cement dropped from 4s/6d per bushel to 1s/3d, while Portland cement remained constant at 2s/6d.[53] Roman cement never regained its former popularity.[54]

Conclusions

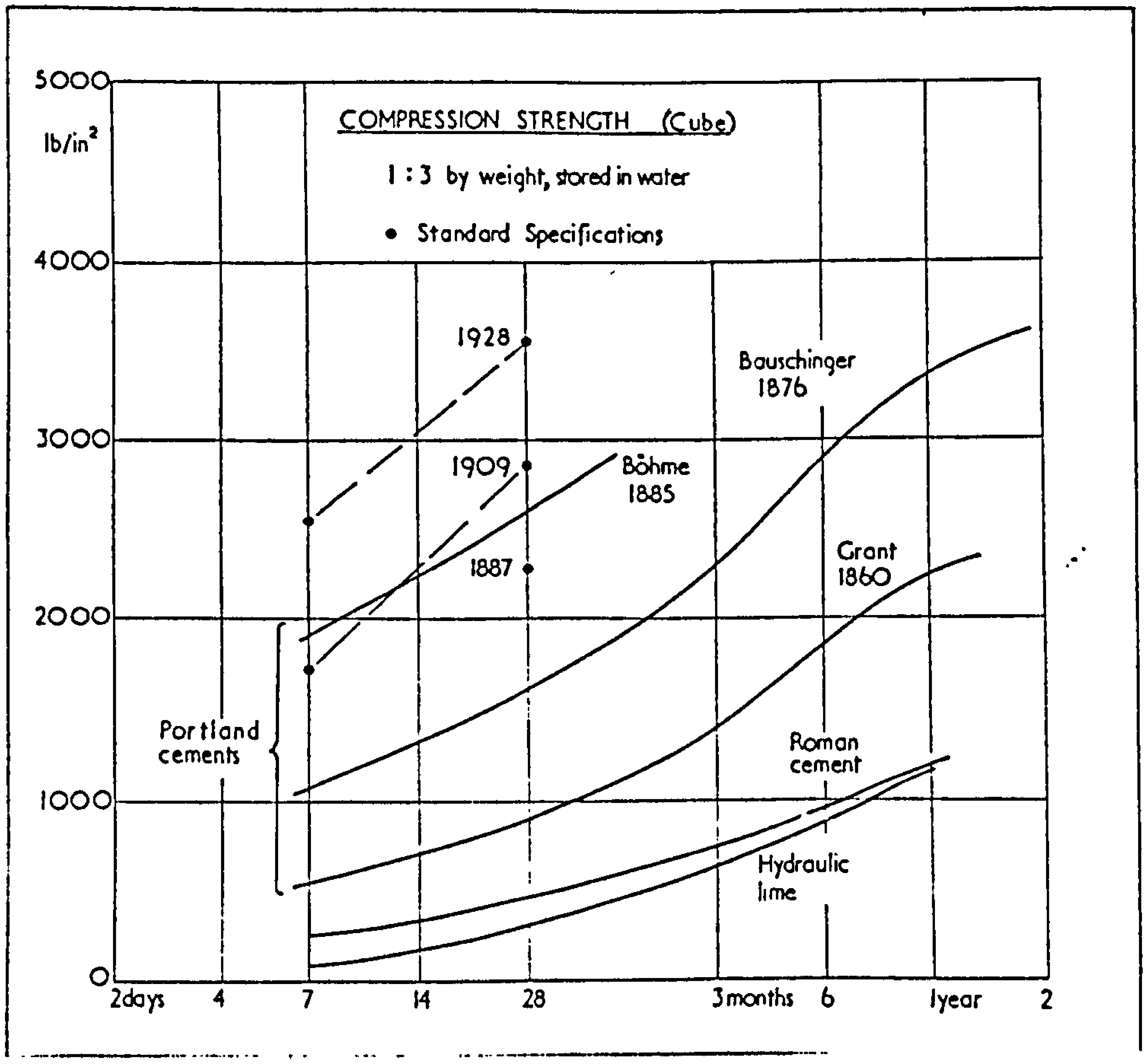
With the slump in the Roman cement industry, the competition between Portland cement manufacturers became intense. The many tests,

TYPICAL PROPERTIES OF LIMES AND CEMENTS

Class (kiln temp.)	Approx. proportion of clay in raw materials, per cent.	Description	Date	Specimens cured in water		Density in loose packing	TENSILE STRENGTH AT 28 DAYS 1:3 BY WEIGHT, lb./sq. in.
				Compression strength at 28 days 1:3 by weight, lb./sq. in.	Time to final set		
"Roman" cements (1,100° C.)	30	Ordinary quality First quality	mid-19th century	300 400	¼ hour	1·0	
Early Portland cements (1,300° C.)	25	Maude and Aspdin J. B. White & Sons Robins and Aspdin English cements English cements	1843 1847 1848 1860– 1865	c. 700 800 1,000± 900 1,200	¼ hour	1·3	–115
Portland cements (1,400° C.)	23	German cements German cements Standard Specifications	1875 1885 1887– 1909 1918 1932 1942	1,650 2,600 2,300 2,800 3,600 3,900 4,500	2 hours	1·3	–228
Hydraulic limes (1,000° C.)	18 15 8	Metz, Teil, Senonches Lias, Labourgade Dorking, Halling	Early and mid-19th century	300 200 100	3 days 6 days 12 days	0·8	
Limes (900° C.)	1	Chalk	—	0	never	0·5	

Table 4: Typical Properties of Limes and Cements

Taken from: Skempton, "Portland Cements," 139 and 147.



Graph 2: Compression Strength of Various Cements

Taken from: Alec W. Skempton, "Portland Cements, 1843-1887," Transactions of the Newcomen Society Vol. XXXV (1962-63), 123.

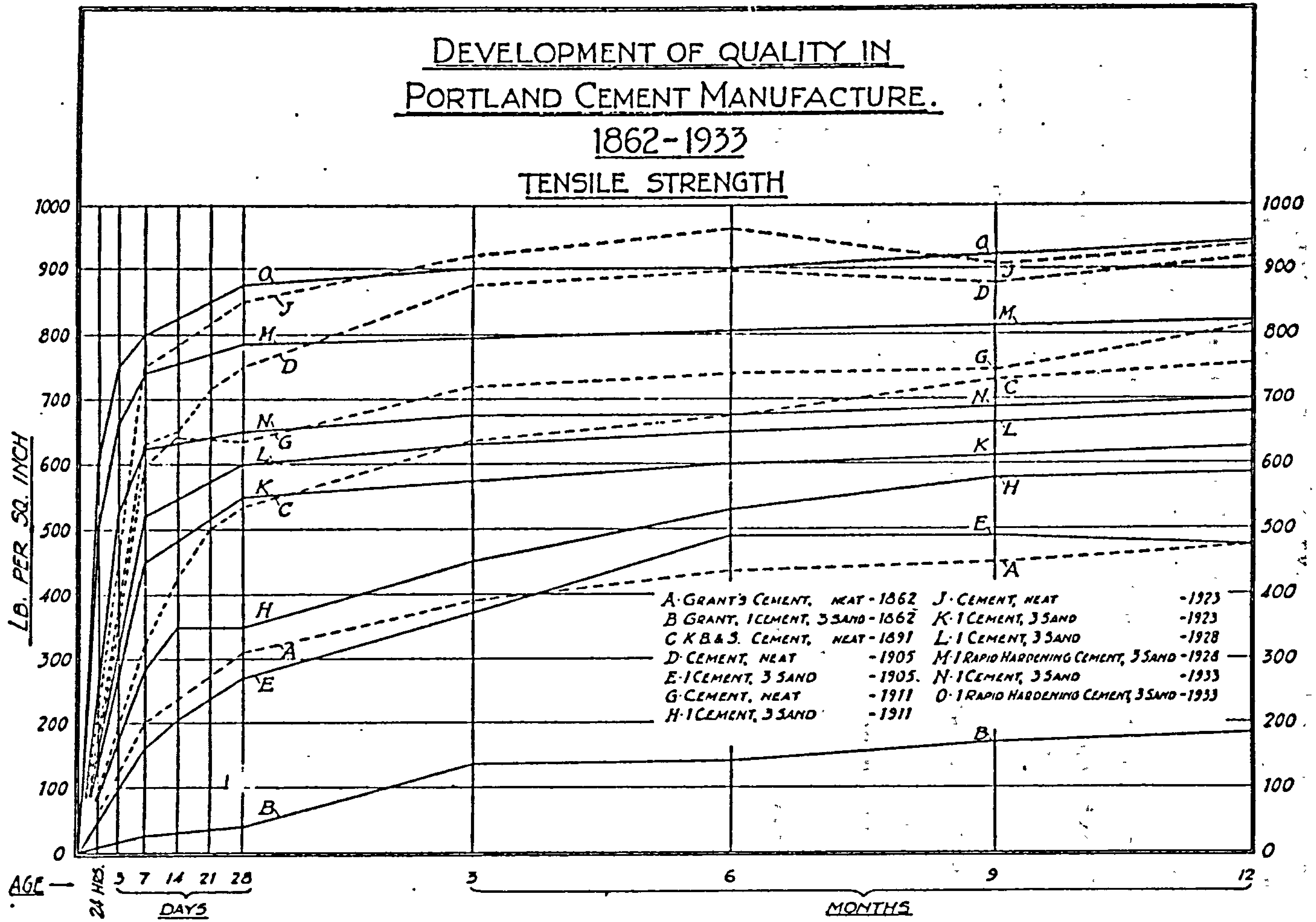


Fig. 1.

Graph 3: Tensile Strength of Various Cements
Taken from: A.C. Davis, Portland Cement (London: Concrete Publications Ltd., 1934), 20.

conducted in the latter part of the nineteenth century, as well as the continuous improvements in kilns and the processes involving them finally brought the cement industry to maturity. By the turn of the century, however, similar advances had been made in other countries, namely France, Germany, and the United States. These exports began hurting the British cement industry, and a depression set in which many men felt only an amalgamation could cure and enable the British to successfully compete in the world market.

In 1900 24 companies combined to form The Associated Portland Cement Manufacturers Ltd.[55] This action did indeed save the British industry and prompted the development of a standardized Portland cement. As a result, in 1904, the first British standard specification for Portland cement, No. 12, was issued.[56]

For the previous 100 years, the cement industry had made major advances in the areas of septaria, vitrification, kilns, and pre-firing techniques called 'wet and dry processes.' Engineers, scientists, and cement manufacturers had debated these issues, striving to determine and achieve the best cement, whether Roman or Portland cement. The final outcome was the Portland cement used today.

References and Notes

1. A.J. Francis, The Cement Industry 1796 - 1914: A History (Newton Abbot: David & Charles Publishers Ltd., 1977), 149.

2. See 'Portland Cement' in Appendix I.

3. Natural cement is defined as a cement made from a naturally occurring single deposit. Henry Cowan, An Historical Outline of Architecture Science (London: Applied Science Publishers Ltd., 1977), 49.

4. Louis J. Vicat, Recherches experimentales sur les chaux de construction, les betons et les mortiers ordinaires. Paris, 1818.

5. Despite its name, Frost's Artificial Cement of 1811 was manufactured as a natural cement. His subsequent patents were true artificial cements. See 'Frost' in Appendix I.

6. Roman cement originally sold at 4s/6d per bushel, while Frost's Cement sold at 1/6 per bushel. Francis, 76, and J. Wylson, "Essay on Mortar and Cements," The Builder, April - June 1844, 725-27.
Some debate occurs as to whether Frost's Cement was cheaper by three shillings because it was an inferior product or because Frost wished to undercut Parker's product. F.M. Lea and C.H. Desch, The Chemistry of Cement and Concrete (New York: Longmans, Green & Co., 1935), 7 vs. Francis, 76.

7. Francis, 62.

8. Louis J. Vicat, A Practical and Scientific Treatise on Calcareous Mortars and Cements, trans. J.T. Smith (London: John Weale, 1837), 111.

9. A. Lipowitz, The Practical Manufacture of Portland Cement, trans. W.F. Reid (London: E. & F.N. Spon, 1868), 13.

10. Besides lack of hardness, the combination of chalk and clay often produced the property of retarded the setting time, which later was often regarded as a useful feature of mortar. Roland A. Paxton, "The Influence of Thomas Telford (1757 - 1834) On The Use Of Improved Constructional Materials In Civil Engineering Practice" (Master's thesis, Faculty of Engineering, Heriot-Watt University, Edinburgh, 1975), 19 and Francis, 208.

11. Paxton, 19.

12. The geological information could be attributed to Smeaton as well as Atkinson himself, who was known by some as "an excellent chemist, geologist and renowned botanist." Francis, 69.

13. Francis, 70.

14. Francis, 69.

15. Paxton, 21.

16. George R. Burnell, Rudimentary Treatise on Limes, Cements, Mortars, Concretes, Mastics, Plastering, etc. (London: John Weale, 1850), 81.

17. I.C. Johnson later disproved this by proving that overburnt cement did set but at a very slow rate and that once set, it was a better cement. Furthermore, in the current production of cements, it is only the clinker produced by incipient vitrification that is retained and used. A.C. Davis, Portland Cement (London: Concrete Publications Ltd., 1934), 6.

18. Burnell, 80-1.

19. Francis, 36.

20. Francis, 37.

21. Paxton, 29-30.

22. A copy of Aspdin's advertisement is reproduced on page 112 of Francis.

23. Francis, 80.

24. Francis, 233.

25. Edwin C. Eckel, Cements, Limes and Plasters (New York: John Wiley & Sons, Inc., 1922), pp. 172-5 and 207.

26. Eckel, 173.

27. Eckel did find it necessary to overlap the index figures for Portland cement and eminently hydraulic limes slightly. Eckel, 204-5.

28. Eckel, 204 and 207.

29. The quantity of coke used in the burning process equalled approximately 40% of the weight of clinker produced. Davis, 104-5.

30. The advancement in the technology of kilns would increase this production figure to 700 tons per week by 1880. Francis, 133.

31. Charles Spackman and Gilbert R. Redgrave, Calcareous Cements: Their Nature, Manufacture, and Uses, with Some Observations upon Cement Testing (London: Charles Griffin & Co. Ltd., 1905), 32.

32. Francis, 138.

33. Francis, 153.

34. Davis, 102-14.

35. Francis, 144.

36. Francis, 231.

37. While it is true that each kiln proved better than the last, especially concerning cement quality, it should be noted, however, that artificial cements had an advantage over the natural cement in that being artificial, their ingredients could be better regulated. Davis, 115.

38. Lipowitz, 28 and Davis, 48.

39. Francis, 143.

40. Lipowitz, 35.

41. Lipowitz says it was also patented by DuPont. Lipowitz, 28 and Davis, 51.

42. It was mentioned briefly in _The Builder_ of 1880 and Lipowitz gave it one paragraph. Lipowitz, 28 and 35; and Francis, 154.

43. Lipowitz, 35.

44. Davis, 51-2 and Francis, 201-2.

45. Davis, 55.

46. In 1825 Brunel began construction on the Thames Tunnel using Roman cement. Francis, 46-7.

47. Wylson, _The Builder_, 725-27.

48. Francis, 47.
This, no doubt, is a journalistic sales pitch since Brunel never wanted to use Roman cement. The directors of the Thames Tunnel Company said this, if anyone did.

49. Professor Skempton believes that Aspdin's cement was sufficiently clinkered to enable it to be termed a 'true' Portland cement. Alec W. Skempton, "Portland Cements, 1843 - 1887", _Transactions of the Newcomen Society_ Vol. XXXV (1962-63), 135.

50. Skempton's paper gives a detailed accounting of Grant's tests and the conclusions reached.

51. Francis, 123-4.
It seems odd that Aspdin should go to Peel when the tax on septaria concerned a rival product, Parker's Roman cement. Aspdin was merely seeking to gain the Government's business and felt this was a good time.

52. The columns were 20' high, 2'2-1/2" in diameter at the base, and 1'10-1/2" in diameter at the capital. Wylson, _The Builder_,

725-27.

53. Wylson, The Builder, 725-27.

54. In 1849, the Roman cement works at Faversham was converted to a Portland cement works. This was one of the many measures manufacturers had to undergo to survive. Skempton, 148. However, Roman cement did remain on the market until at least 1870, but was limited to pointing and stuccoing. Francis, 65 and Skempton, 148.

Augustus W.M. Pugin once stated that Roman cement was not even suitable for stucco. In 1822, James Wyatt used brown Roman cement in the restoration of the west front of Lichfield Cathedral. In 1833, Pugin noted that the cement was cracking in many directions. Martin S. Briggs, Goths and Vandals (London: Constable and Co., Ltd., 1952), 157. Despite all the negative points raised against Roman cement, the fact remains that the Thames Tunnel was largely constructed with it and the tunnel stands today, with the minimum of repairs, to prove it.

55. The British Portland Cement Manufacturers Ltd. followed in 1911, amalgamating 33 additional individual companies. Francis, 307-10.

56. Francis, 257-66.

Chapter 3: 'Organic' and 'Synthetic' Additives in Mortars

Introduction

While lime and cement mortars have dominated the building industry over the centuries, there has been a third type of mortar employed regionally. Termed 'organic mortars,' these consisted of natural ingredients found locally and were used in lieu of the limes and cements due to prohibitive costs and scarcity.[1]

These latter deterrents are no longer of consequence, and 'organics' are now rarely used. A similar form of mortar additive has, within the last few decades, replaced 'organic' ingredients and has succeeded in retaining a third option of mortar on the market. Termed 'synthetic mortars,' they appear to be outgrowths of the 'organics,' both chemically and physically.

While the use of 'synthetics' is relatively new and has only existed in this century, 'organic' materials have been employed for over 2000 years in various countries all over the world. Their repeated and wide-spread use could only have continued if the success rate was relatively high. This is substantiated by the frequent mention of specific 'organics' in treatises and other works through the ages; authors had written down their observations and opinions on the use of 'organic' additives in mortars.

The property(ies) each 'organic' was to impart can be determined from the documentation, and it may be compared against that (those) claimed by the manufacturers of comparable 'synthetic(s).' The pros and cons of each 'organic' vs. 'synthetic' can be examined in two ways: by their physical effect on mortar properties, and by their chemical composition. This analysis will yield some knowledge on the employment of 'organics' in mortars and how 'synthetics' are functioning as their replacements.

Documentation

Surviving documents dating back as far as Vitruvius's Ten Books on Architecture were the main keys to compiling a complete list of 'organic' materials used in mortar.[2] In addition to enabling a time-of-use value, based on popularity, to be calculated, these works often mentioned the physical properties the various 'organics' brought to a mortar. Occasionally they elaborated further and gave an explanation as to why one material was preferred over another. In total, the data gleaned from these literary sources helped to form a picture of the use of 'organic' additives in mortars.

One commonly mentioned property was the setting quality. Literature stated that certain 'organics' either 'regulated' the set or 'retarded' the set of a mortar. The word, regulate, was not clearly defined. George P. Bankart in his work, The Art of the Plasterer, wrote that juice of figs, rye dough, hogs' lard, curdled milk, blood, and the whites of eggs were employed in Vitruvius's time to toughen and regulate setting qualities.[3] ('Toughen' is often used in conjunction with 'harden' and 'coagulate.') Pliny's Natural History, however, listed two of the above 'organics,' hogs' lard and figs, as 'mollifiers' or 'plasticizers.'[4] Thus it can be deduced that 'regulate' may be defined as 'to put in good order' or 'to make a mortar workable.'[5]

Retarding the set of a mortar was as important as increasing its workability. Bankart stated that blood and egg whites, in addition to 'regulating' a set, also retarded it.[6] These two additives, as seen in Table 5, proved to be the most popular 'organics' over the ages. The fact that they served to improve both the workability and the time during which it remained workable may be the cause of their popularity.

Some retarders also carried the property of increasing the hardness or durability of a mortar. Sugar, saccharine, fruit juices, rice, and gluten were used for both these properties in India and Ceylon in the Middle Ages.[7]

'Hardness' was another desired property, though this word had a variety of meanings, not limited to any geographic area. In Italy,

Table 5: List of 'organic' materials and their dates. From L.B. Sickels, "Organic Additives in Mortars," in E.A.R., Vol. 8, 1981, p. 15.

	150 BC Egyptian	46 BC Vitruvius' time	23 AD Pliny	800 AD Rochester Cathedral	1200 Middle Ages	1500	1653 Plat	1703 Neve, Moxon	mid-1700s	1837 Vicat, Smith	1850 Burnell & periodicals
albumen	X										
animal glue	X							X			X
barley			X						X		
beer					X	X			X		
beeswax					X	X		X	X		X
blood	X	X	X	X		X	X	X	X		X
butter										X	
buttermilk									X		
casein	X										
cheese								X	X	X	X
cotton											X
curdled milk		X							X	X	
dung									X		
eggs	X				X	X		X	X		X
egg whites	X	X			X	X	X	X		X	X
elm bark			X								
fibers			X								
fig juice	X	X	X						X		
fruit juices					X	X			X		
gluten					X	X			X		
gum arabic	X					X	X				X
hair			X								
hogs' lard		X	X					X			X
keratin	X										
malt					X	X					
milk		X	X					X	X	X	X
molasses										X	
oil			X							X	X
resin								X			
rice					X	X					
rye dough		X							X		
saffron			X								
shellac											X
size			X		X	X					
suet			X								
sugar					X	X				X	
tannin			X								
urine					X	X					
vegetable juice									X		
wine			X								
wort					X				X		

Pliny used the word to refer to acceleration in setting as well as durability with time. "The blood of the bull coagulates and hardens the most speedily of all...Cow's milk immediately following a birth is 'colostra,' and will coagulate and assume the hardness of pumice."[8] In France in 1837, Vicat also referred to hardness as a synonym for durability and acceleration of set.

> In those situations in which it is impossible to avoid the use of rich limes, it may be useful to be aware that their bad qualities may be in some degree corrected, by the use of a comparatively small quantity of the coarsest sugar dissolved in water with which they are worked up. This substance (or 'jaghery') is extensively employed in the East...for the common mortars made of calcined shell...resist the action of the weather for centuries; and I have no doubt that this is in great part to be attributed to the use of sugar, the influence of which on the first solidification of the mortar is very marked. Even in this country it may occasionally be found advantageous to employ the cheapest sugar, or molasses, when works of importance have to be stuccoed with rich lime; for its aid is chiefly confined to the hardening of the outer surface...[9]

Vicat implied that sugar accelerated the first solidification of a mortar, and yet Bankart stated that sugar was used to retard a set. Both men were discussing the employment of sugar in the East, particularly India, when they listed its setting property. Without tests, it would be hard to determine who was right.

Accelerating a set means shortening the time the mortar takes to achieve a firm set. This is necessary when a mortar will be carrying a greater weight sooner than normally expected, or when the possibility of frost exists. On the other hand, retarding a set increases the time a mortar takes to achieve its set and permits the mortar to remain workable longer. These two properties, as deduced from literature, were known in India, Italy, France, and Great Britain, suggesting that seasonal changes were experienced in all locations. Table 6 shows average high and low temperatures experienced in these countries. With the exception of Ceylon and India, freezing and thawing were known to most countries, though not in all cities within a country. The lowest monthly mean temperature in Rome, Italy, for example, is 39°F, while

Temperatures (°F) in Various European and Asian Countries

H = aver. daily high
L = aver. daily low
P = # of days w/ rain

File: Table 6:

Page 1

Report: Temperatures (F)

Jan. 15, 1985

Country	City	Jan			Feb			Mar			Apr			May			June			July			Aug			Sept			Oct			Nov			Dec		
		H	L	P	H	L	P	H	L	P	H	L	P	H	L	P	H	L	P	H	L	P	H	L	P	H	L	P	H	L	P	H	L	P	H	L	P
Ceylon	Colombo	86	72	7	87	72	6	88	74	8	88	76	14	87	78	19	85	77	18	85	77	12	85	77	11	85	77	13	85	75	19	85	73	16	85	72	10
England	Liverpool	44	36	18	44	36	13	48	38	13	52	41	14	58	46	14	63	51	13	66	55	15	65	55	16	61	51	15	55	46	17	48	41	17	45	37	18
England	London	44	35	17	45	35	13	51	47	11	56	40	14	63	45	13	69	51	11	73	55	13	72	54	13	67	51	13	58	44	14	49	39	16	45	36	16
France	Biarritz	54	40	10	52	38	11	63	43	11	63	44	11	69	53	11	72	56	10	80	66	7	77	61	7	77	58	9	74	55	11	58	44	12	53	41	14
France	Bordeaux	48	35	16	52	36	14	58	40	12	63	44	15	69	49	15	75	54	13	80	58	11	80	57	10	75	54	12	66	47	13	55	41	16	49	37	17
France	Le Havre	45	36	16	48	37	14	52	39	15	58	43	14	65	47	13	70	52	11	74	56	12	73	56	14	70	52	14	61	47	16	52	41	16	47	38	17
France	Marseille	53	38	10	52	37	9	55	38	8	59	41	10	65	46	10	72	52	9	78	58	6	83	61	4	82	61	5	76	57	7	67	50	10	59	43	11
France	Nantes	45	36	11	49	36	11	54	38	12	61	42	9	67	46	10	73	53	9	77	56	8	77	55	7	72	51	7	62	45	13	52	39	13	46	36	14
France	Nice	56	40	8	56	41	8	59	45	8	64	49	7	69	56	8	76	62	5	81	66	2	81	66	5	77	62	6	70	55	9	62	48	7	58	43	8
France	Paris	42	32	15	45	33	13	52	36	15	60	41	14	67	47	13	73	52	11	76	55	12	75	55	12	60	50	11	59	44	14	49	38	15	43	33	17
India	Bombay	83	67	<1	83	67	<1	86	72	<1	89	76	<1	91	80	1	89	79	14	85	77	21	85	76	19	85	76	13	89	76	3	89	73	1	87	69	<1
India	Calcutta	80	55	<1	84	59	2	93	69	2	97	75	3	96	77	7	92	79	13	89	79	18	89	78	18	90	78	13	89	74	6	84	64	1	79	55	1
Ireland	Belfast	45	34	19	47	34	18	49	35	20	53	39	18	59	43	17	64	49	10	66	51	18	65	51	20	62	48	17	55	42	19	50	37	21	46	35	25
Italy	Bridisi	55	43	10	57	43	6	60	45	5	65	50	5	73	57	5	80	64	2	84	68	1	84	69	3	80	65	4	70	58	8	64	52	10	58	46	8
Italy	Florence	49	35	9	53	36	9	60	40	7	68	46	7	75	53	9	84	58	5	89	63	4	88	62	4	81	58	6	69	51	9	58	42	10	50	37	9
Italy	Milan	40	29	7	47	33	6	56	38	6	66	46	6	72	54	9	80	61	6	84	64	6	82	63	6	76	58	6	64	49	7	51	39	7	42	33	7
Italy	Naples	54	42	11	55	43	11	60	46	6	67	50	6	73	56	6	81	62	3	86	67	1	86	67	3	81	63	6	72	56	4	63	49	11	57	45	11
Italy	Rome	54	39	8	56	39	11	62	42	5	68	46	6	74	55	6	82	60	3	88	64	2	88	64	2	83	61	6	73	53	9	63	46	8	56	41	9
Italy	Venice	43	33	6	46	35	5	54	41	6	63	49	5	71	57	8	78	64	8	82	67	8	82	67	5	78	62	5	65	52	7	54	43	7	46	37	7
Netherlands	Amsterdam	40	34	19	41	34	15	46	37	13	52	43	14	60	50	12	65	55	12	69	59	14	68	59	14	64	56	15	56	48	18	64	52	6	57	46	7
Scotland	Edinburgh	43	35	18	43	35	15	47	36	15	50	39	16	55	43	15	62	48	15	65	52	17	64	52	17	60	48	16	53	44	18	47	39	18	44	36	17
Turkey	Ankara	39	24	8	42	26	8	51	31	7	63	40	7	73	49	7	78	53	5	86	59	2	87	59	1	78	52	3	69	44	5	57	37	6	43	29	9

Taken from: Franc Shor, ed., National Geographic Atlas of the World (Washington, D.C.: National Geographic Society, 1970), pp. 180-81.

in Milan it falls as low as 29^{o}F. In India it never freezes, but the monsoons of summer would suggest the need for an accelerator in the mortar. Of all the countries listed, Great Britain experiences the most frost changes with an average of 1.5 to 2 per day.[10]

A final property, commonly mentioned in literature, is binding. Many authors stated that various 'organics' were employed as binders, and today this word is more typically defined as 'adhesives' or 'tackifiers,' and occasionally, 'strengtheners.' The particular 'organic' served to tack or adhere the other mortar ingredients together, possibly giving the mortar additional strength. In his book, The Technical Arts and Sciences of the Ancients, Albert Neuburger discussed the use of 'organic' additives based on analyses of ancient building materials. He listed gum arabic or tragacanth, animal glue from Rhodes, the blood of the hippopotamus, and the milky juice of figs mixed with the yellow of the egg as binding substances.[11] Egg albumin, keratin, and casein were other common Egyptian natural 'organic' polymeric binders.[12]

Sir Hugh Plat gave an example of a 'binder' by stating in his 1594 book, The Jewel House of Art and Nature: "Temper Ox-blood and fine clay together and lay the same in any...wal, and it will become a very strong binding substance."[13] The blood adhered to the clay and the mixture strongly tacked itself to the surrounding wall units. Plat also gave a recipe for making a substitute for gum arabic, listed by Neuburger as a binder. "Beat the Whites of diver Egges into a thin and clear oly [sic] or water; put the same into bladders, and hang them in your kitchen chimney, where a fire is usually kept in the day time, and in a few days the same will become as hard as gum Arabick."[14]

'Organics,' over the centuries, became known for their properties; they served as retarders, adhesives, plasticizers, accelerators, strengtheners, and perhaps even solidifiers and air entrainers. These properties were largely associated with the preparation of a mortar and its early use rather than the long-term effects. This indicates that the main use of 'organic' additives in a mortar may have been to obtain a set, leaving the lime and other ingredients to harden slowly by drying and carbonation.

From the discussed literature, Table 5 was compiled, listing some of the more common 'organic' components. By documenting their dates of use by the sources, a pattern emerges of the popularity and continued use of 'organic' materials over the centuries. Blood was the one 'organic' that was used continually for nearly 2000 years. Eggs, egg whites, and milk were almost equally popular, experiencing only short periods of non-use. Table 7 was also compiled, listing the property by name, its desired effect, and the 'organic' vs. 'synthetic' equivalents. The relative success rate of mortars made with these 'organic' additives, together with the availability of the 'organics,' led to their sustained use up to and, in some areas, into the twentieth century.

Chemistry of the 'Organics'

'Organic' materials were not selected for use in mortars based on their chemical composition. Many were chosen for the obvious physical properties they imparted such as the coagulating effect of blood, or the plastic or gelatin-like quality of egg whites. By qualitatively examining popular additives, one may begin to draw conclusions as to <u>why</u> various 'organics' remained in use longer than others.

The 'organics' listed in Table 5 were classified and examined for common elements. A pattern emerged. The 'organics' used the most frequently over the centuries contained high levels of the simple proteins: albumins and globulins. Over half of the 'organics' contained one of these or other simple proteins, indicating that polyamides were present.[15] Such substances as sugar and cotton are comprised largely of polysaccharides, which are also polyamides. Examination of the chemical structure of polyamides, particularly proteins and polysaccharides, helps one understand their functions in mortars and the effect they have on other constituents in the mix.

Proteins and polysaccharides are polymers made up of complex chains of amino acids. They differ, however, in that the main bonding chain

Table 7: A list of selected admixtures for possible use in mortars (and plasters).*

Type of admixture	Desired effect	'Organic' material	'Synthetic' material[a]
accelerator	accelerate setting and early strength development	egg whites elmbark barley water fig juice rye dough hogs' lard curdled milk blood starch colostra gum mastic sugar	calcium chloride triethanolamine calcium formate epoxies urea with barium hydroxide
adhesive/ tackifiers	increase bond	rosin gelatin animal glues esp. hides gluten vegetable glues casein blood albumen	acrylic resins acrylic polymer acrylic emulsion epoxy polymer rubber butadiene-styrene copolymers polyvinyl chloride (PVC) polyvinyl acetate (PVA) PVA with PV alcohol
air entrainer	improve durability	malt beer urine animal hides	alkyl-aryl sulphonates salts of lignosulphonates alkylbenzene sulphonates barium hydroxides sulphonated hydrocarbons

* The named materials in this table are a combination of pure elements and compounds.

[a] Some of these synthetics may need an additional synthetic in order to impart the required properties (e.g. air entrainers).
See Footnote 1 of this chapter for author's use of 'organic' and 'synthetic.'

Table 7 cont.

Type of admixture	Desired effect	'Organic' material	'Synthetic' material
emulsifier/ stabilizer	stabilises an emulsion (use in small quantities)	egg yolk oils fats waxes	benzophenones[b] benzotriazoles acrylonitriles
filler	improve hardness	size glue gum arabic talc sugar saccharine fruit juices rice	coarse fluid coke acrylic polymer acrylic emulsion sodium borosilicate glass
frost resistor	resistance against frost penetration	sugar	polyethylene acrylics propyl alcohol
modifiers	alters existing solution	egg whites hemp seed blood gluten keratin collagen casein gelatin resins	acrylic polymer acrylic emulsion acrylic powder polyvinyl acetate (PVA) water-soluble resins formaldehyde cellulose derivatives triethylene glycol glycol ester styrene/butadiene copolymers pyrogenic silica

[b] These synthetics are used to stabilize an emulsion against ultra-violet light; they are UV absorbers.

Table 7 cont.

Type of admixture	Desired effect	'Organic' material	'Synthetic' material
non-shrinking agents	prevents shrinkage	beeswax	fluid coke aluminum powder silica gel acrylic polymer acrylic emulsion
plasticizer/ mollifier	impart plasticity reduce brittleness; a softener increase workability	sugar milk egg whites slurried dung Turkey red oil animal glue mineral oil rosin non-drying oils: linseed oil hogs' lard figs	hydroxylated carboxylic acids salts of lignosulphonates silicones Vinsol resin or phenol-formaldehyde resin[c] sodium borosilicate glass epoxies phosphates glycolates polybutenes phthalates acrylic emulsion acrylic polymer
retarder[d]	retards setting time	sugar blood egg whites	lignin tartaric acid and salts silicones hydroxylated carboxylic acids
solidifier/ rigidifier	increase hardness or stiffness	sugar vegetable glues[e] animal glues treacle molasses	silicones silane coupling agent baryta polyurethanes

[c] Vinsol resin is also an extender.

[d] Some retarders may carry air entrainers or have the properties known to air entrainers.

[e] Upon exposure to the sun, vegetable and animal glues become rigid.

Table 7 cont.

Type of admixture	Desired effect	'Organic' material	'Synthetic' material
strengthener/ binder	improves strength of solution	keratin casein elmbark hot barley water tannin size linseed oil walnut oil cow/ox/human hair chopped straw rice rye dough[f] egg whites fibrin in blood cotton flock jute sisal gum arabic or tragacanth animal glue fig juices with egg yolks sugar	acrylonitrile acrylic emulsion acrylic polymer nylon fluid coke polyvinyl chloride (PVC) polyvinyl acetate (PVA) polyethylene terephthalate polythene propyl alcohol
superplasticizer	high flow	albumen	melamine formaldehyde sulphonates naphthalene formaldehyde sulphonates
thickener	thickens the consistency of an emulsion	blood sour milk casein cheese collagen gelatin gum tragacanth with water	pyrogenic silica acrylic emulsion

[f] The use of rye dough requires a non-shrinking agent.

Table 7 cont.

Type of admixture	Desired effect	'Organic' material	'Synthetic' material
waterproofing, dampproofing and weatherproofing repellent.	decrease permeability	animal glue plus tannin bitumen wax emulsion mineral oil emulsion beeswax	soluble chlorides calcium stearate aluminum stearate ammonium stearate methyl groups stearic acid oleic acid polyurethanes[g] polysylphide sealant epoxy resins with silicones epoxy-terminated polyurethanes silicones silane coupling agent silicone resin with mineral spirits sodium methyl siliconate with water polyvinyl acetate (PVA) fluid coke acrylic resins

[g] Polyurethanes are generally replacing polysulphides.

Sources: Banov, Abel. Paints and Coatings Handbook. Farmington, MI: Structures Publishing Co., 1978.
Canadian Building Digests. Ottawa: National Research Council of Canada, 1973+.
Design and Control of Concrete Mixtures. Skokie, Ill.: Portland Cement Association, 1979.
The Conservation of Cultural Property, XI. Paris: The United Nations Educational, Scientific, and Cultural Organization, 1979.

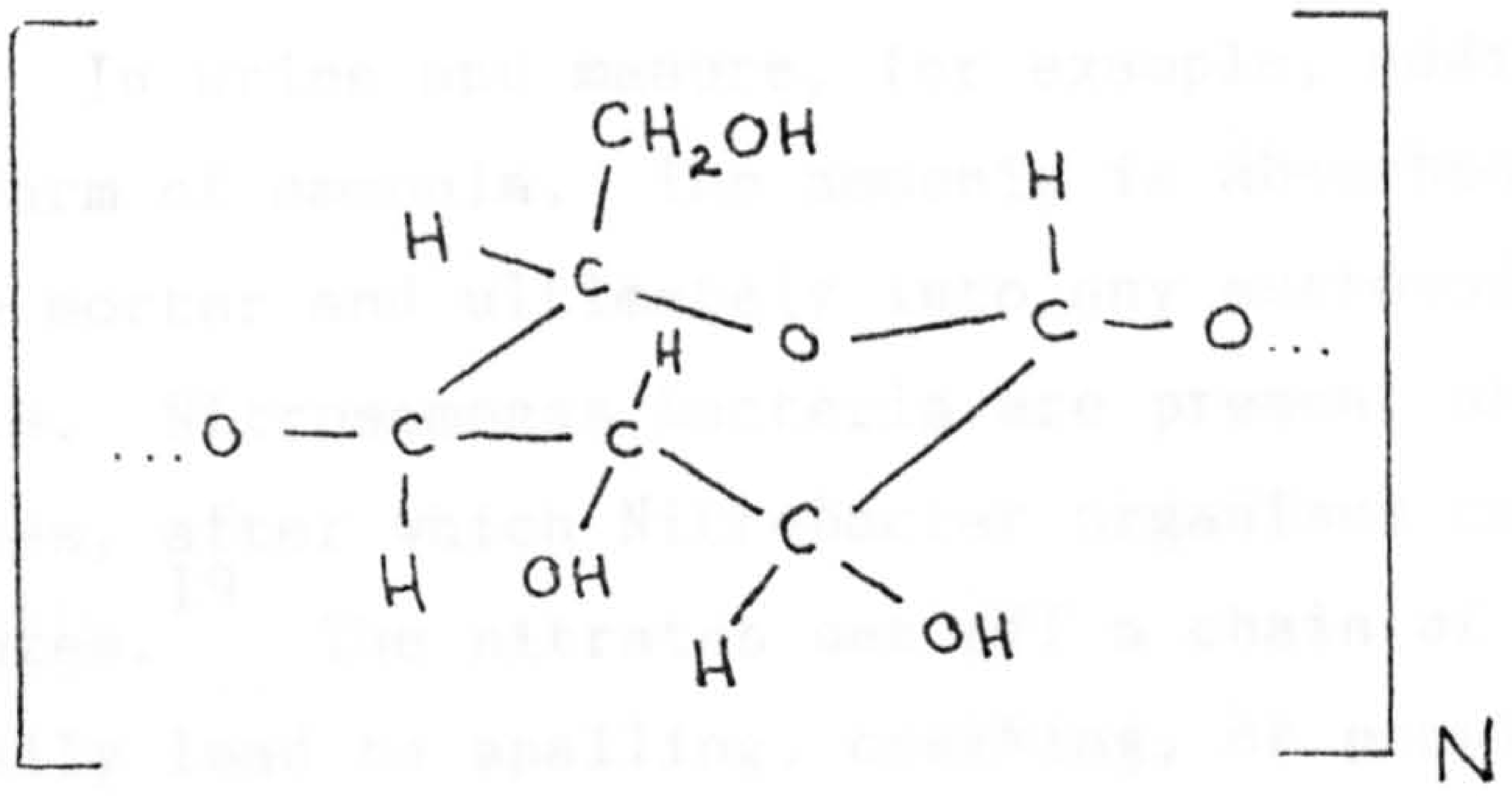
for proteins consists of carbon and nitrogen, while that of the polysaccharides is comprised of carbon and oxygen (Figure 5). The structure of the chains can be long and narrow, or folded and twisted. The fibrous or stretched-out form, called the 'beta' form, is common to such proteins as blood. The spherical or folding form, named the 'alpha' form, is common to such proteins as keratin, the protein of hair and wool (Figure 6).[16] Both forms are stabilized by such weaker chemical forces as hydrogen bonds.

The structural state of these two polyamides makes them favorable for use in a mortar. When combined with lime and sand the folded or fibrous chain intertwines itself around the lime and sand particles.[17] This reaction, initially, creates a fairly hard, firm mortar. However, it is not unusual for a protein or polysacchride to alter its existing state abruptly due to such changes in the environment as temperature or alkalinity. These changes increase the risk of fracturing the chain bonding, particularly in the weaker secondary bonds. The rupture of one bond facilitates the rupture of others, and while the bonds continually try to mend, they will never reach a stable state if the source of disorganization is not removed.[18] Mortars made with 'organic' additives are susceptible to these alterations.

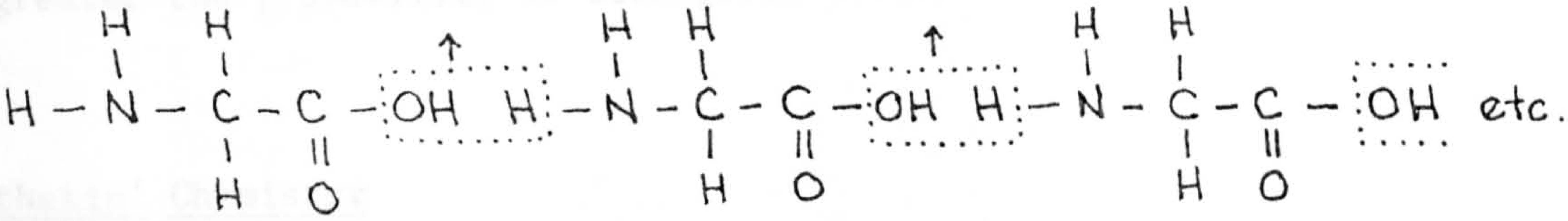
'Organic' Decomposition

The bonded nitrogen and oxygen in 'organic' mortars attract plants and detritus-feeding organisms. It was previously stated that these two elements, with carbon, comprise the polymer chains of proteins and polysaccharides respectively. Nitrogen and oxygen are the elements which bacteria and other micro-organisms feed on, thus causing the imbalance and eventual collapse of the polymer chains and therefore, the mortar.

Nitrogen, in particular, causes extensive damage to a mortar in an indirect way. Proteins contain approximately 16% nitrogen and through a sequence of events, this relatively high level attracts plants, one of their main food sources being nitrogen. Lichens and other



Cellulose, a polysaccharide



A protein made from 3Glycine

Figure 5

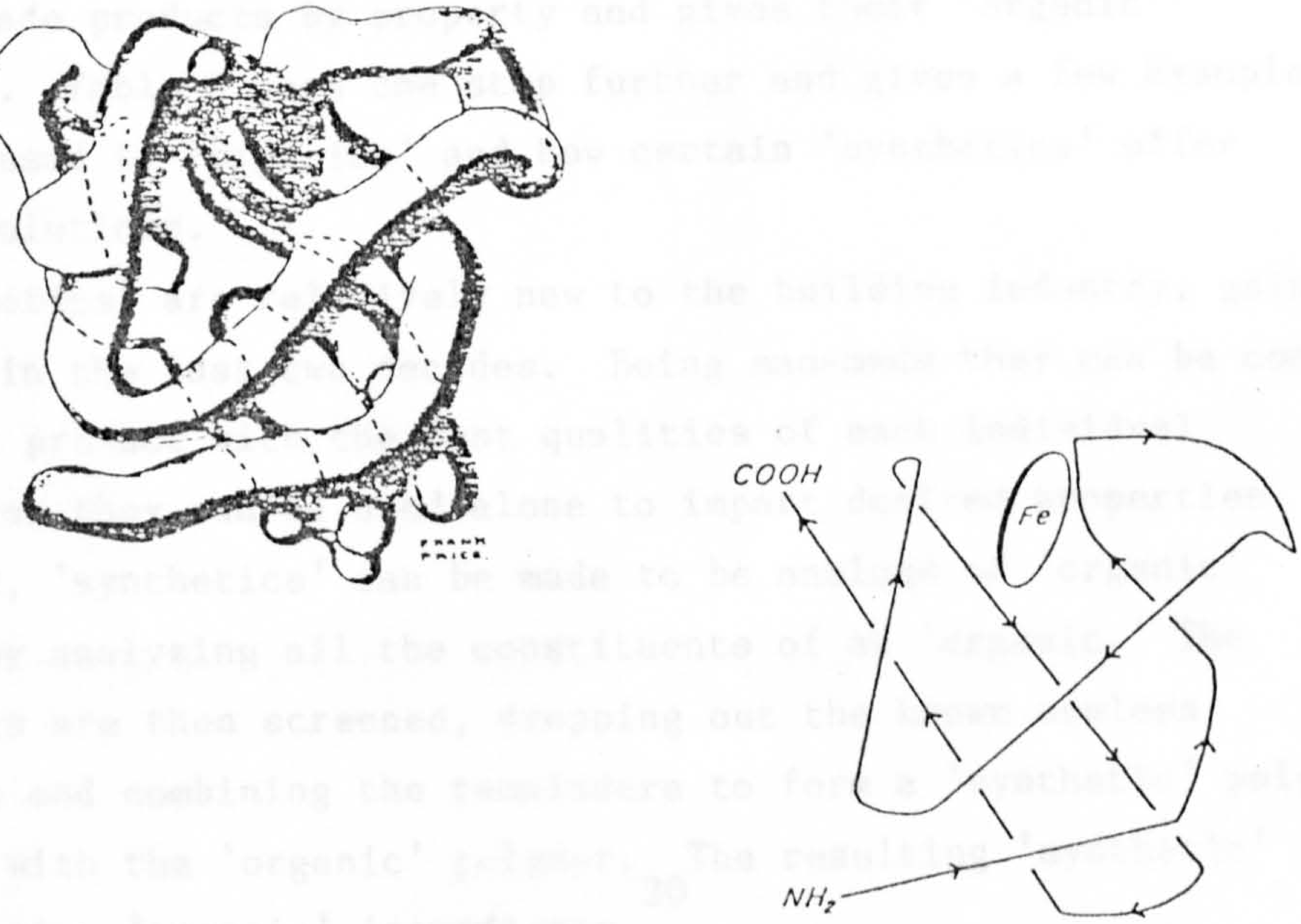


Figure 6: The Alpha form.

Taken from: Aaron M. Altschul, Proteins (London: Chapman and Hall, Ltd., 1965), p. 68.

micro-organisms are also encouraged by any 'organic' with a high nitrogen content. In urine and manure, for example, additives, nitrogen is found in the form of ammonia. The ammonia is absorbed into the other components of the mortar and ultimately into any surrounding porous building materials. Nitrosomonas bacteria are present and convert the ammonia to nitrites, after which Nitrobacter organisms convert the nitrites to nitrates.[19] The nitrates set off a chain of events which can eventually lead to spalling, cracking, or popping mortar.

Table 8 provides a list of 'organics' and their approximate percentage of nitrogen content. The higher the nitrogen level becomes, the greater the probability of biological breakdown of the mortar.

'Synthetic' Chemistry

The ideal alternative to an 'organic' mortar is a material which is compatible in chemical and physical structures with the 'organic' and yet is not subject to biological attack or decay. 'Synthetics' are claimed by manufacturers to meet these expectations. Table 7 lists these man-made products by property and gives their 'organic' equivalents. Table 9 goes one step further and gives a few examples of problems caused by 'organics' and how certain 'synthetics' offer favorable solutions.

'Synthetics' are relatively new to the building industry, gaining popularity in the last two decades. Being man-made they can be combined to create a product with the best qualities of each individual component, or they can be used alone to impart desired properties. In either case, 'synthetics' can be made to be analogs of 'organic' additives by analyzing all the constituents of an 'organic.' The constituents are then screened, dropping out the known useless ingredients and combining the remainders to form a 'synthetic' polymer synonymous with the 'organic' polymer.[20] The resulting 'synthetic' is based on active 'organic' ingredients.

'Synthetics' are largely divided into two groups: thermoplastics and thermo-setting plastics. Both groups are polymers or polyamides and

Material	Nitrogen Content (%)
Hair	17.70
Albumen	15.70
Egg white	15.10
Urine	15.00 - 18.00
Buttermilk	14.80
Curdled milk	14.40
Blood	10.00 - 14.00
Poultry manure	6.30
Meat Scraps	5.10
Sheep manure	3.75
Pig manure	3.75
Lettuce	3.70
Cabbage	3.60
Tomato	3.30
Cotton	3.00
Onion	2.65
Cheese	2.30
Horse manure	2.30
Turnip tops	2.30
Raw garbage	2.15
Farmyard manure (average)	2.15
Bread	2.10
Eggs	1.90
Seaweed	1.90
Cow manure	1.70
Wheat flour	1.70
Barley	1.60
Whole carrot	1.60
Mustard	1.50
Potato tops	1.50
Rice	1.30
Fern	1.15
Whole turnip	1.00
Timothy	0.85
Milk	0.50
Sugar	0.20

Table 8: Nitrogen Content of Various Organics.

Table 9: Selected examples of 'synthetic' alternatives.

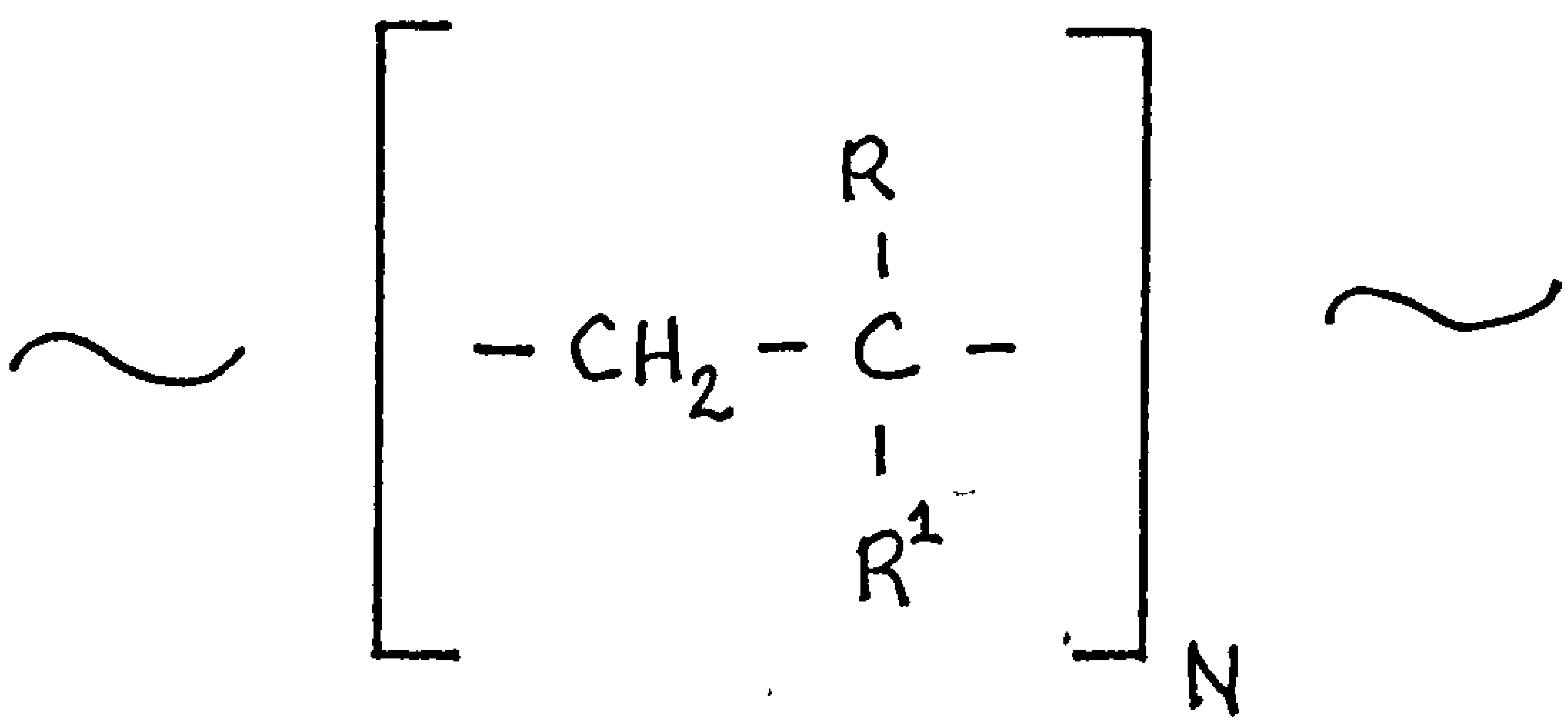
Type of admixture	'Organic' material	Problem	'Synthetic' solution
adhesive	rosin	yellows	epoxy polymer
air entrainer	urine	lichen growth	polyethylene oxide
plasticizer	linseed oil	low film strength at low temperatures	acrylate copolymers: PVA
strengthener	tannin	soluble in water	acrylic emulsions
thickener	blood	red or dark stain attracts insects, rodents, vampires	pyrogenic silica
waterproofer	casein	not outstanding resistant to hydrolysis, oxidative deterioration or microbiological attack	silicones silane coupling agent

are formed from reactions between simple molecules. The main portion or backbone of the polymer is composed of carbon atoms alone, whereas the 'organic' backbone was comprised of carbon, and nitrogen or oxygen. The 'organic' polymers contained in mixtures in Table 7 are stereoregular, meaning that the side chains form a regular pattern across the carbon backbone. By having this regularity the polymer can achieve better properties such as higher strengths and better chemical resistance. Furthermore, some can withstand extreme temperatures without disintegrating.[21] To prepare a synthetic polymer, a catalyst is introduced to promote orderly reactions and growth within the polymer, thus maintaining the necessary regularity.[22] For example, nylon, a thermoplastic, is formed from the amino ($-NH_2$) and carboxylic acid ($-COOH$) groups; urea, a thermoset or amino resin, is produced by the reaction of the amino ($-NH_2$) with formaldehyde.[23]

The first group, thermoplastics, is based on linear branched polymers, typical of the 'beta' form described for 'organic' additives. The general formula of thermoplastic polymers is given in Figure 7, showing the close association these 'synthetics' have with some of the 'organics.' With the application of heat, thermosets become more rigid and thermoplastics less rigid. The main difference between thermoplastics and thermosets is that the former do not undergo any irreversible chemical changes when they are heated and cooled.[24]

Thermosetting polymer components consist of molecules with permanent cross-links between linear chains that form a rigid three-dimensional network structure.[25] This arrangement is more closely related to the 'alpha' form described for 'organic' additives and indicates a state of minimum energy where the ability to crystallize, a common property of most man-made polymers, is at its lowest.[26] Figure 8 shows an example of a thermoset formula, again showing the close association it maintains with some of the 'organics.'

Epoxy polyester is an excellent example of a combination of thermoplastics that can be used, in connection with a mortar, as an adhesive, an additive, or a protective surface coating. Each of the two components can be varied to achieve required characteristics. By increasing the proportion of polyester, solvent and acid resistance can

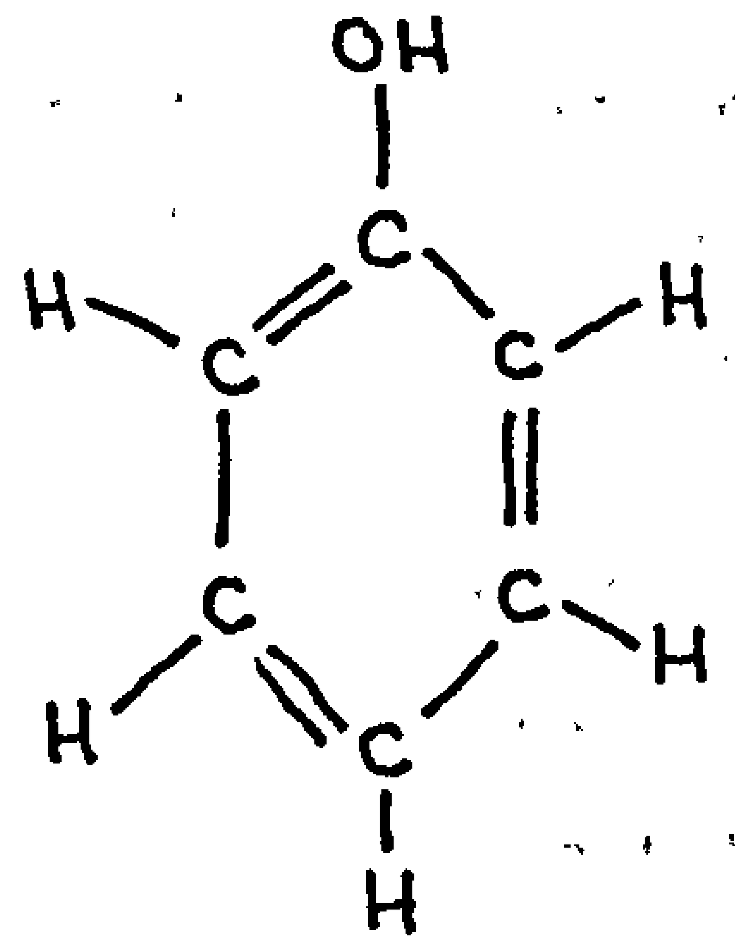


Thermoplastic Polymers with a C-C Backbone Chain

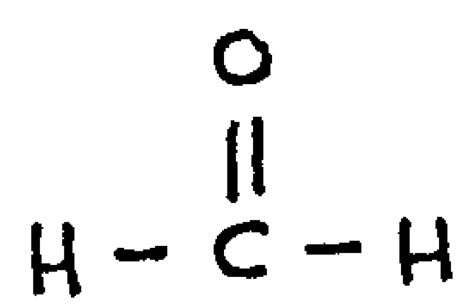
R	R^1	Name of Polymer	Abbreviation
H	H	Polyethylene	PE
H	CH_3	Polypropylene	PP
H	Cl	Polyvinyl chloride	PVC
H	C_6H_5	Polystyrene	PS
H	$COOCH_3$	Polymethyl acrylate	PMA
CH_3	$COOCH_3$	Polymethyl methacrylate	PMMA

Figure 7: General Formula of Thermoplastic Polymers having a C-C Backbone Chain

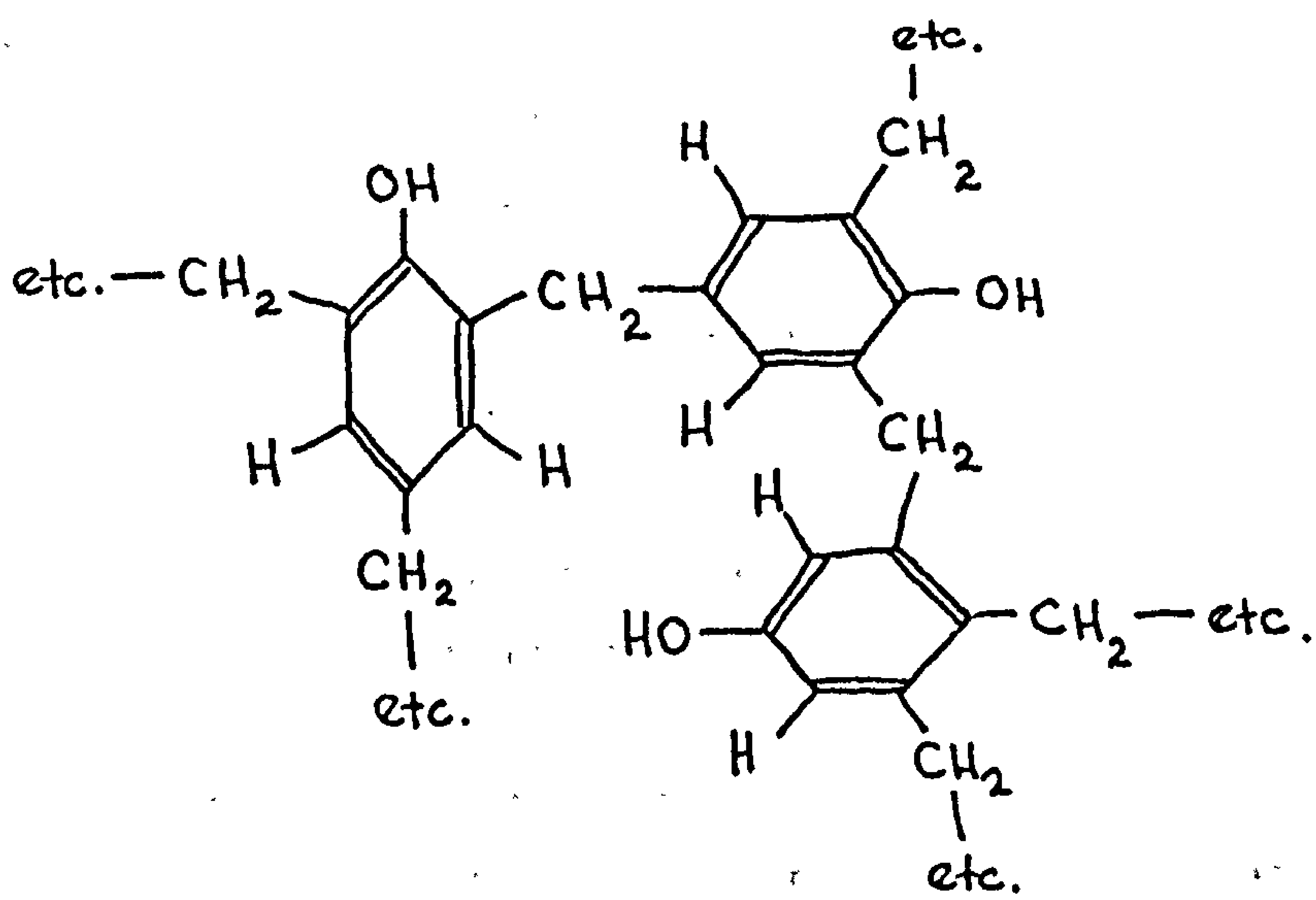
Taken From: A. Blaga, Canadian Building Digest #158: Thermoplastics (Ottawa: National Research Council of Canada, 1974), p. 158-2.



Phenol



Formaldehyde



Together, they form Phenol-formaldehyde resin

Figure 8: A Thermoset Chain

be increased. By increasing the proportion of epoxy, gloss retention, flexibility, adhesion, and alkali resistance are enhanced. Furthermore, the setting time of epoxy polyesters can be controlled by regulating the two components.

Acrylics and polyvinyl acetate (PVA) have shown considerable promise in the field of mortar additives as single components, not necessarily requiring an additional constituent. Among the various 'synthetics' available as alternatives to 'organics,' these two carry the qualities of color stability, stability against expansion and contraction over a wider temperature range, and additional strength to a mortar to enable it to resist weathering.[27]

Conclusion

'Synthetics' have not been in use long enough for their long-term behavior to be known. These observations can only be made after decades of exposure in practice. Both 'synthetic' thermoplastics and 'synthetic' thermosets are outgrowths of the 'organics' as their chemical and physical structures are similar. 'Synthetics' are more resistant to attack and decay from biological organisms. They have, however, been largely confined to use with cement, while 'organics' were used largely with lime.

Written information about the use of 'organic' additives over the centuries has indicated which ones were used repeatedly and what properties they were intended to impart. The technology of the twentieth century has permitted manufacturers of 'synthetic' additives to produce analogs of many of these 'organics.' Time alone will tell if a 'synthetic' alternative is successful, but for now it does provide a third type of mortar in addition to lime or cement mortars.

References and Notes

1. 'Organic' and 'synthetic,' for the purpose of this chapter, have meanings somewhat different from strict dictionary definitions. 'Organic' is a term used to describe all materials, except pozzolana, found in a natural state. Pozzolana is eliminated as it was a lime substitute in Italy. The 'organic' additives tended to be used with a lime in a mortar. These additives are usually unadulterated before being combined with other materials in a mortar. 'Synthetic' is a term used to describe both man-made materials and natural materials which have been adulterated or pretreated by man in some way before being employed in a mortar.

2. For a historical account of the literature discussing 'organics,' see: Lauren-Brook Sickels, "Organic Additives in Mortars," in Edinburgh Architecture Research, vol. 8, 1981, pp. 7-20.

3. George P. Bankart, The Art of the Plasterer (London: B.T. Batsford, 1908), pp. 6-7.

4. Kenneth C. Bailey, The Elder Pliny's Chapters on Chemical Subjects, vol. II (London: Edward Arnold & Co., 1932), p. 143; and John Bostock and H.T. Riley, The Natural History of Pliny, vol. III (London: Henry G. Bohn, 1860), p. 9.

5. Guralnik, David B., ed. Webster's New World Dictionary (New York: The World Publishing Co., 1972), p. 1638.

6. Bankart, 6-7.

7. Bankart, 7.

8. Bostock, 79 & 84.

9. Louis J. Vicat, A Practical and Scientific Treatise on Calcareous Mortars and Cements, artificial and natural, trans. Colonel J.T. Smith, R.E. (London: John Weale, Architectural Libary, 1837), p. 84.

10. Bernard M. Feilden, Conservation of Historic Buildings (London: Butterworth Scientific, 1982), p. 105.

11. Albert Neuburger, The Technical Arts and Sciences of the Ancients, trans. Henry L. Brose (London: Methuen & Co., Ltd., 1930), p. 199.

12. Edward V. Sayre, "Deterioration and Restoration of Plaster, Concrete and Mortar," in Preservation and Conservation:

Principles and Practices, ed. Sharon Timmons (Washington, D.C.: The Preservation Press, 1976), p. 192.

13. Sir Hugh Plat, The Jewel House of Art and Nature (London: Elizabeth Alsop, 1653), p. 72.

14. Plat, 44.

15. A 'simple' protein is defined as any protein which yields only alpha-amino acids on hydrolysis. A polyamide is a polymer in which the monomer units are linked together by the amide group: -CONH-. Roger J. Williams, An Introduction to Organic Chemistry (New York: D. Van Nostrand Company, Inc., 1935), pp. 301-2.

16. Aaron M. Altschul, Proteins (London: Chapman and Hall, Ltd., 1965), p. 64.

17. Interview with Dr. R.O. Gould, lecturer in Chemistry Department, University of Edinburgh, Scotland, August 17, 1982.

18. Altschul, 70.

19. John R. Lewis, College Chemistry (New York: Barnes & Noble Books, 1971), p. 200.

20. Interviews with Dr. Mae Beck, chemist, Cambridge, Massachusetts, March 1 and June 16, 1984.

21. The listed 'synthetics' in Table III are not stereoregular, but it is not known if this is an advantage or disadvantage.

22. R.W. Moncrieff, Man-made Fibres (London: Newnes-Butterworths, 1975), p. 117.

23. A. Blaga, Canadian Building Digest #158: Thermoplastics (Ottawa: National Research Council of Canada, 1974), p. 158-4; and A. Blaga, Canadian Building Digest #159: Thermosetting Plastics (Ottawa: National Research Council of Canada, 1974), p. 159-4.

24. Blaga, 158-1.

25. Blaga, 159-1.

26. Patrick Meares, Polymers: Structure and Bulk Properties (London: D. Van Nostrand Co., Ltd., 1965), p. 20.

27. Blaga, 158-4.

Chapter 4: Case Studies

Introduction

Case studies are an important adjunct to laboratory research. They provide real-life examples to support test results obtained within a controlled environment. To prove useful, however, each case must be carefully and completely surveyed.

Thus, a 3-page form was designed and used to provide information on wall behavior (Figure 9). A sample of a completed form is given in Appendix 4. All repairs regardless of age were examined, and as much topographical and climatic information as possible was compiled to give a thorough understanding of the structure and its environment.

In addition to the survey form, the following seven questions were considered when each crack or craze was inspected.

1. Is the crack solitary or from a pattern?
2. Is there another crack in the same relative position in another portion of the structure performing a similar duty?
3. What is the depth of the crack?
4. Does it come out on the opposite side of the member?
5. Is the inside face of the crack new or old looking?
6. Is the crack live or dead?
7. Does the crack relate to changes in the use of the structure?[1]

The direction and inclination of each crack were noted as indications of their cause.

--Open horizontal cracks indicate vertical settlement.
--Open vertical cracks indicate horizontal movement.
--Converging cracks upward show settlement of lintel.
--Diverging cracks upward show outward leaning or the failure of foundations.
--Bowing or bulging walls, spalling angles, or over-stressed joints indicate expansion and compression.
--Parallel, very fine, vertical cracks indicate vibration.[2]

MORTAR SURVEY Background Information	Address: Country:

IDENTIFICATION

Original Owner:
Present Owner & Address:

Original Building Name:
Present Building Name:

General Topography/Zoning/Direction:

Original Use:
Current Use:

Date of Construction:
Dates of Alterations (describe):

Architect(s):
Style:
Size/Bays/Storeys:
Building Materials:

Original Mortar Components:
Original Mortar Proportions:

Source of Information:

RESTORATION

Architect(s):
Supervisor:

Date Work Undertaken: By:

Type of Repair Work: Bedding: Repointing:

Location of Repairs:

Specification Requirements for Mortar:

New Mortar Components:

New Mortar Proportions:

Thickness of Joint: Uniformity:

REMARKS

Date:	By:	Case Study No.	Sheet No.

Figure 9

MORTAR SURVEY Further Restoration Information	Address: Country:

RESTORATION/REPAIR NO. 2	Architect(s): Supervisor: Date Work Undertaken: By: Type of Repair Work: Bedding: Repointing: Location of Repairs: Specification Requirements for Mortar: New Mortar Components: New Mortar Proportions: Tickness of Joint: Uniformity:
RESTORATION/REPAIR NO. 3	Architect(s): Supervisor: Date Work Undertaken: By: Type of Repair Work: Bedding: Repointing: Location of Repairs: Specification Requirements for Mortar: New Mortar Components: New Mortar Proportions: Thickness of Joint: Uniformity:
FURTHER REMARKS	

Date:	By:	Case Study No.	Sheet No.

MORTAR SURVEY Performance Information	Address: Country:

DETERIORATION

Age of Repair at Time of Observation:

Problem:	Yes	No	Location on Building Material:	Size:	Source/Cause:
Cracking:					
Crazing:					
Spalling:					
Efflorescence:					
Staining:					
Coheson of New to Old:					
Bond of Joint Itself:					
Pigmented:					
Aggregate:					
Inorganic:					
Uniformly colored:					
Other:					

DIAGRAMS OF DAMAGE

Diagrams of Damage
(not to scale)

ENVIRONMENT As Applied to Building Exposure

General Area Weather Statistics:

Specific Site Topography:

Effects from:
- Wind:
- Water:
  - Rain:
  - Rising Damp:
  - Other:
- Sun:
- Frost:
- Ground:
- Biological Sources:
- Other:

REMARKS

Date:	By:	Case Study No.:	Sheet No.:

After completing the survey forms and analyzing any cracks present, the case studies were compiled and written up to contain historical and restoration information. The cases are presented in the following pages, grouped according to their mortar proportion.

Edinburgh Castle

Historical Background:

The summit of Castle Hill, overlooking the city of Edinburgh, Scotland, has served as the location for a Royal fortress and home for over eight centuries (Figures 10 & 11). The hill with its subsequent castle was favored by kings and queens for its natural defensive formation, and it also had springs and green pastures for cattle on its slopes.

Supposition states that an Iron Age fort existed on the summit and was used by Pictish kings. St. Margaret's Chapel is the oldest surviving structure of Edinburgh Castle. This and other structures served as the main residence of King Malcolm III (d. 1093) and Queen Margaret (d. 1093). Their son, David I (1084 - 1153), and subsequent heirs resided in the castle on a frequent basis. As a result, Edinburgh Castle became a meeting place for Councils and other assemblies, and became the storehouse for treasures and records of the crown.

William the Lyon (1143 - 1214) was King of Scotland when the castle was first captured by the English in 1174. Henry II (1133 - 1189) claimed this and three other fortresses and retained them until his death and the marriage of William in 1189. In 1296, the castle was again besieged and taken by the English, remaining in their hands until 1313 when Thomas Randolph (d. 1332), nephew of Robert the Bruce (1274 - 1329), recaptured it.

When David II (1324 - 1371) became King of Scotland while still a minor, the English again occupied the castle. In 1341, posing as merchants, William of Douglas and others gained entrance to the fort and attacked, taking back the castle for King David. David II began to rebuild Edinburgh Castle in 1367. Further attempts were made on the castle in the reigns of Robert II (1316 - 1390) and Robert III (1340 - 1406).

By the time James IV (1473 - 1513) gained the throne, the castle was no longer fit for a royal residence. The Queen Dowager chose to repair the fortification in 1514, after which it once again served the Royal family. In 1517 James V (1512 - 1542) sought safety there and

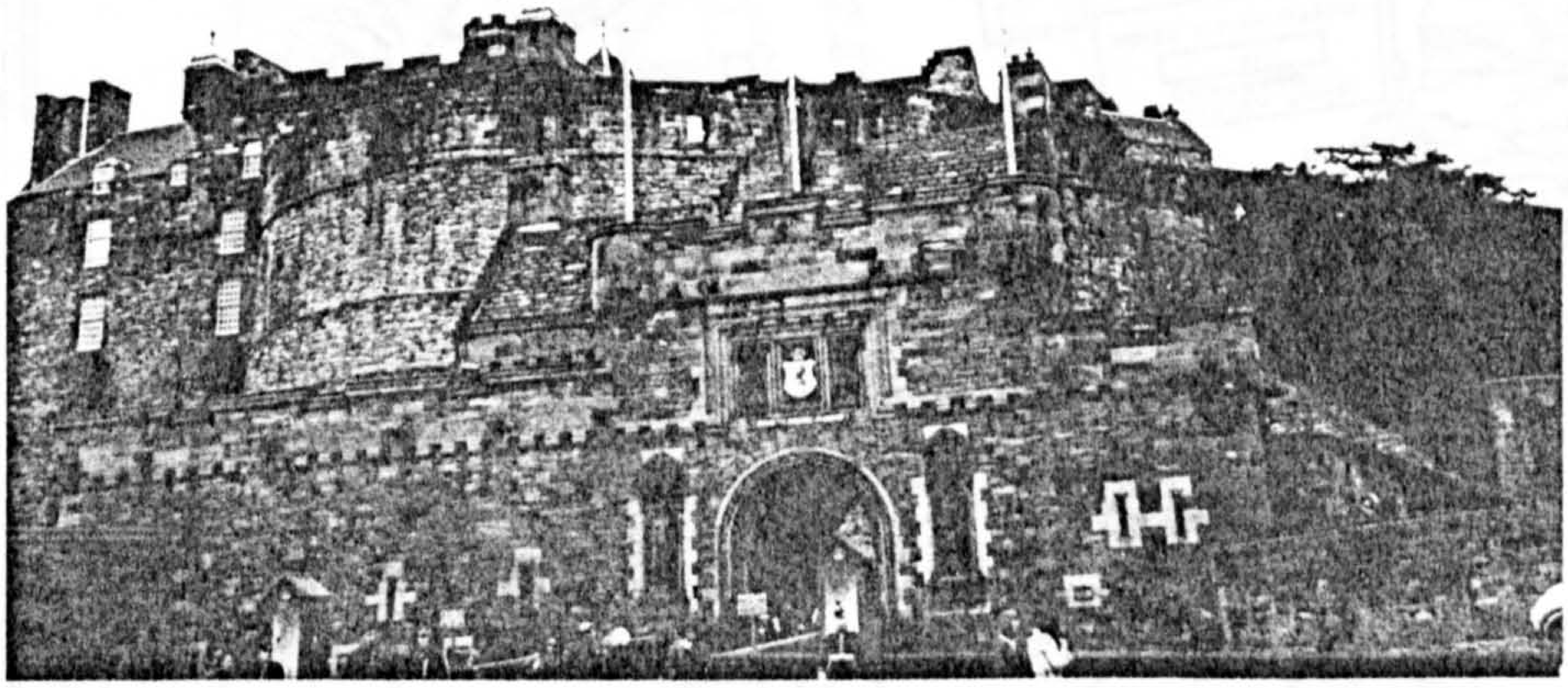


Figure 10

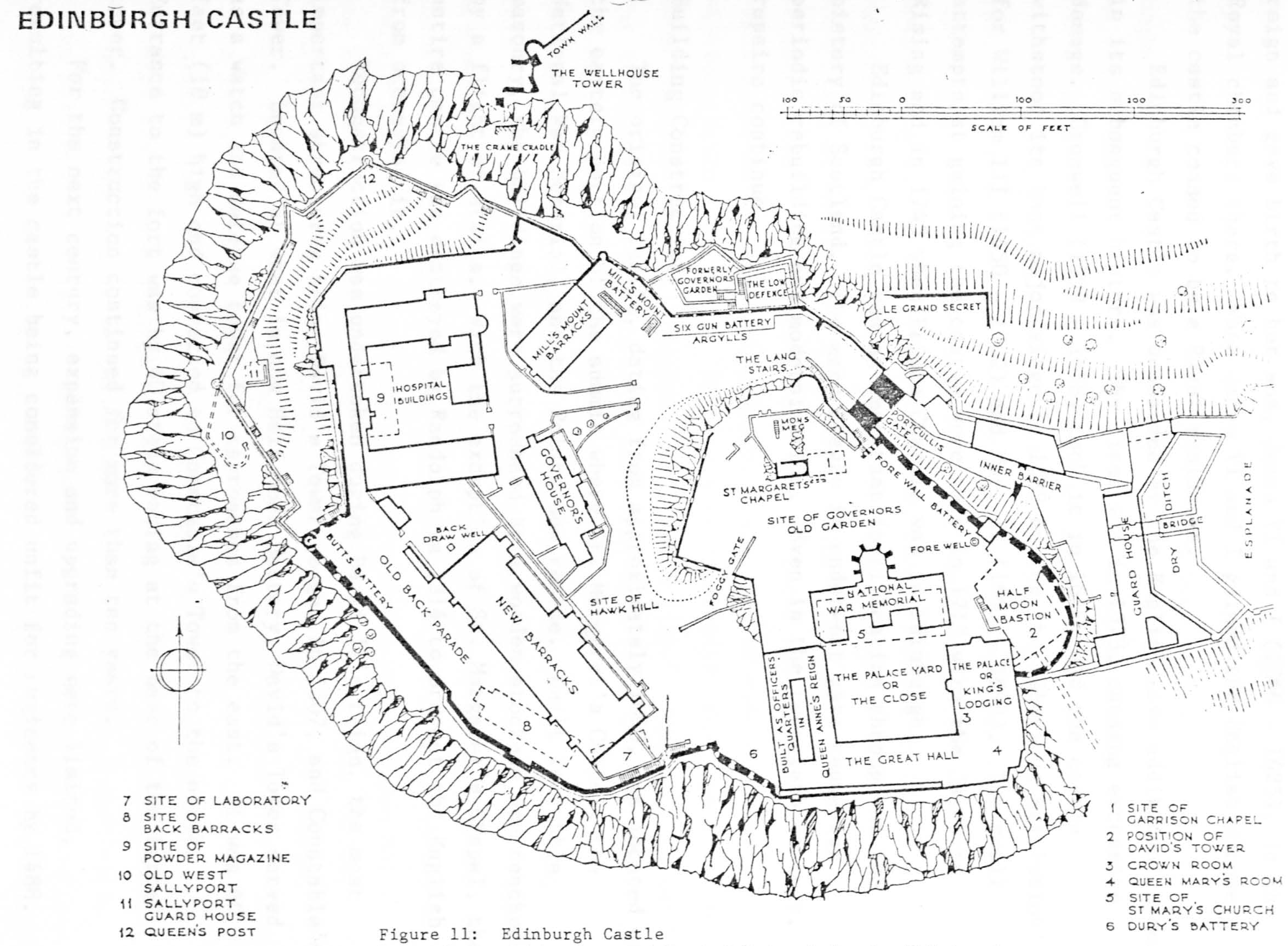


Figure 11: Edinburgh Castle
Taken from: Richardson and Wood, Edinburgh Castle (Edinburgh: Her Majesty's Stationery Office, 1953), p. 18d.

later after his death, his widow, Mary of Lorraine (1515 - 1560), resided there. Their daughter, Mary (1542 - 1587), Queen of Scots, frequently sought shelter in Edinburgh Castle during the turmoils of her reign and gave birth to her son, James VI and I (1566 - 1625), in the Royal chambers there. When James VI and I gained the English throne, the castle ceased to be a Royal residence.

Edinburgh Castle was bombarded by the English five additional times in its subsequent history. The first was in 1573, causing extensive damage. Cromwell (1599 - 1658) took it in 1650, and the castle withstood its last major siege in 1689 during the 'Glorious Revolution' for William III (1650 - 1702) and Mary II (1662 - 1694). Two small attempts at gaining the castle were made in 1715 with the Jacobite Rising and in 1745 when Prince Charlie was in Edinburgh.

Edinburgh Castle was an important fortification throughout the history of Scotland. The many sieges it underwent gave cause for periodic rebuilding and modernization. Even in the twentieth century, repairs continue.

Building Construction:

The original castle, dating from approximately 1060, was located on the eastern portion of the summit where St. Margaret's Chapel, the National War Memorial, and the Palace now reside. Built in rubble masonry, the buildings were surrounded by a wooden stockade and reached by a flight of stairs. With the exception of St. Margaret's Chapel, the entire castle was destroyed by Randolph in 1314 to prevent the English from occupying it.

Reconstruction was undertaken during David II's reign, the most important structures being David's Tower, begun in 1367, and Constable's Tower. Located at what is now Half Moon Battery, David's Tower served as a watch and defense tower for approaches from the east. It was 60 feet (18 m) high and connected to Constable's Tower to the north. Entrance to the fort was by 40 steps ending at the base of the latter tower. Construction continued for more than ten years.

For the next century, expansion and upgrading were limited, resulting in the castle being considered unfit for residency by 1488.

Later in the fifteenth century, modifications were made to the Palace, particularly the King's Lodging. In 1514 the Captain of the Castle wrote to the Queen Dowager asking for permission to redesign and rebuild the fortification. Permission granted, the Captain ordered the repair of exterior walls and construction of a bakehouse and brewhouse.

The Long Siege of 1573 began in April with five batteries bombarding the castle night and day. On May 22nd David's Tower collapsed and before the Siege was over, Constable's Tower was destroyed and considerable damage was done to the exterior walls.

Rebuilding began almost immediately and by 1574, the Portcullis Gate had been erected by Regent Morton. The present roadway leading to the Palace yard was also constructed for the conveyance of artillery. Despite the fact that the castle was no longer considered a Royal residency, King James VI and I, nevertheless, had additional portions of the Palace remodelled and heightened in 1615 - 1617 at a cost of £25,000 Scots. Undertaken by the King's Master Mason, William Wallace, stone-vaulted beer cellars, elevations of rubble masonry, and platform roofs were built. Wallace used Innerleith Craig sandstone and stone quarried "bewest from Sanct Cuthbert's Kirk." Oystershells used for pinnings came from Newhaven; lime came from Kirkliston; and sand and sea clay arrived from Leith.[3]

Despite the earlier work, a southern portion of the castle wall fell on November 20, 1639, weakening the gun embrasures located there. The wall was immediately repaired, but damaged again during Cromwell's invasion. In 1662 Robert Mylne, the King's Master Mason, fixed the wall and the embrasures. In 1677 another contract was made between Mylne, the King's Engineer, the King's Cash Keeper, and others for further repairs. A report was made in 1679 on the condition of the castle, finding the stonework of the batteries and a house near the Great Hall to be in bad states of repair. General upgrading was also required.

Before all the work could be finished, Edinburgh Castle was again besieged and bombarded in te Spring of 1689. Part of the magazine and the west sallyport were battered down, and a guardroom was destroyed. Mylne returned to carry out the repairs and make further modernizations in 1692-3. Apparently not everything was completed, for in 1728 General

Wade reported that the castle walls were in a ruinous state.

By 1751 more buildings were being constructed, particularly the North Barracks. Later the Scottish National War Memorial was erected on the site of the barracks, incorporating part of the older walls. Finally, the Esplanade was built in the early nineteenth century.

Repairs:

The twentieth century has been spent restoring and repairing the castle as it existed. Edinburgh Castle houses some of Her Majesty's military forces and serves as some of the offices for the Scottish Development Department. The S.D.D. has been responsible for upkeep and until approximately 1970, the standard mortar mix and ratio was 1:1:2 Arden, Scotland hydraulic lime:pebbles:sharp sand. When the lime from Arden became obsolete in 1970, hydraulic lime from France was substituted and the mix was altered to 0:1:2-3 hydraulic lime:quarry sand.

Typical repairs using Arden lime were made around 1960 to the north wall of the King's Lodging and the walls of the old North Barracks (or War Memorial). Applied to rubble masonry, the mortar was pointed into the joints at various depths, so that the new joints ranged from flush to recessed about ½ inch (1¼ cm). On one random rubble wall, the joints were made flush, then scored into straight joints with a tool (Figure 12). On another wall the S.D.D. included pebbles in the mix as they felt it aesthetically enhanced the rubble walls (Figure 13).

Observations:

Only the repairs carried out in the twentieth century can be monitored as previous repairs were infrequent and the mortar mixes used are unknown. The work done using Arden lime and later, French hydraulic lime, has weathered well over the 20 years. No cracking or crazing is visible on the walls specified above. Moreover, where the joints are flush, there are no signs of the sandstone rubble deteriorating.

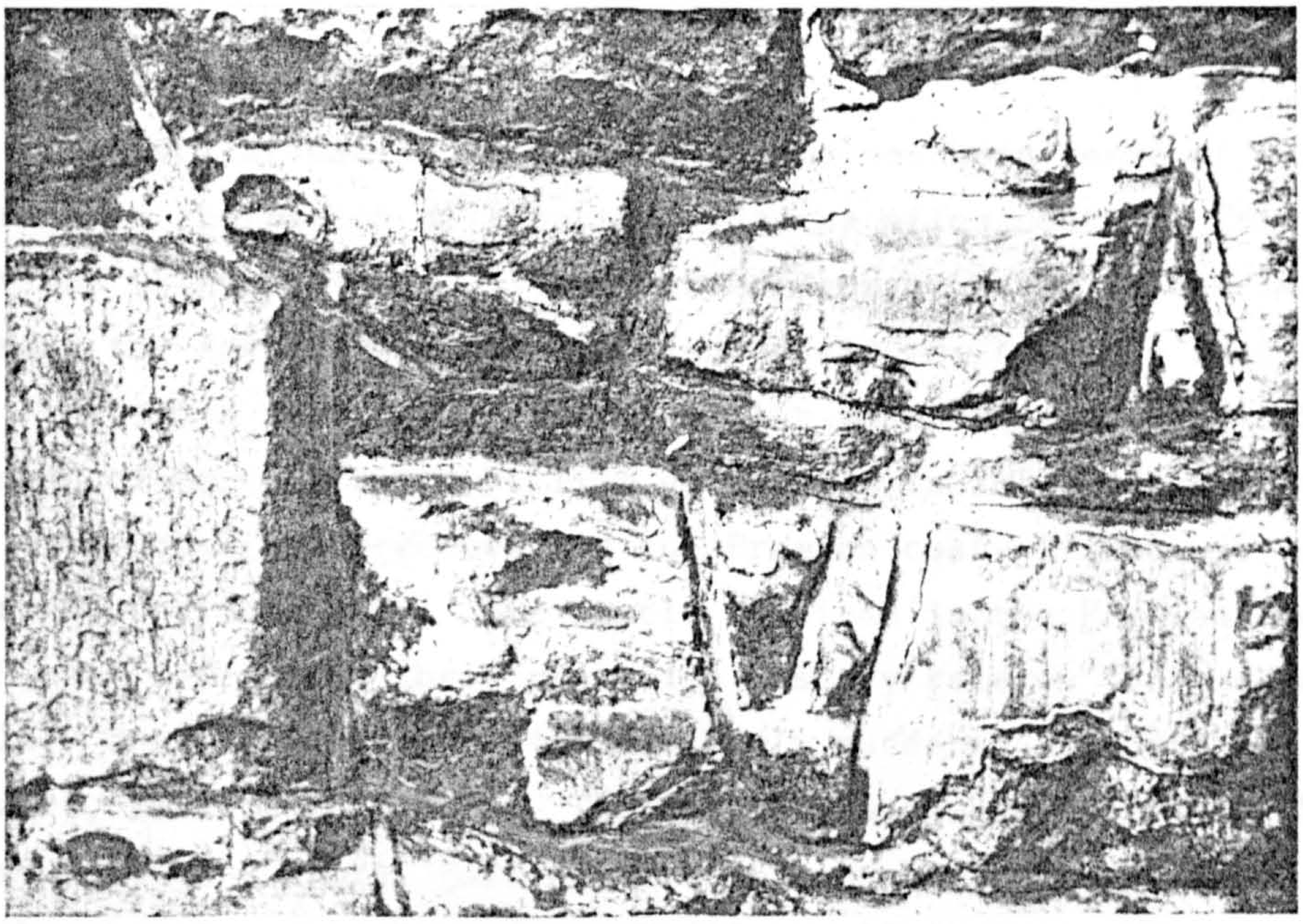


Figure 12

Figure 13

Craigmillar Castle

Historical Background:

Craigmillar Castle is located on the southern verge of a 30-foot (9 m) rock in the parish of Liberton, several miles south of Edinburgh, Scotland (Figures 14 and 15). Like Edinburgh Castle it has served as a retreat for Royalty and has experienced sieges, but on a smaller scale.

The lands and barony of Craigmillar were acquired by Sir Simon Preston of Gorton from a William de Capella in 1374. Shortly thereafter the towerhouse was erected, and the Preston coat-of-arms was rendered over the entrance door. The castle remained in the Preston family until 1660, but over these three centuries history records four major events. In 1477 James III (1451 - 1488) secretly murdered his brother, John Stewart, Earl of Mar, here. The castle was sacked in 1544 by Edward Seymour (1506 - 1552), Earl of Hertford, on his Scottish march to burn Edinburgh. As a boy King James V (1512 - 1542) was taken to Craigmillar when Edinburgh raged with the plague. And, Mary, Queen of Scots, withdrew to the peace and quiet of Craigmillar after the murder of David Rizzio (1533 - 1566) in 1566, while at the same location others planned the murder of her husband, Lord Darnley (1545 - 1567).

The Barony of Craigmillar was sold to Sir John Gilmour in 1660. Gilmour was President of the College of Justice and was involved in obtaining mercy for the Covenanters. In 1761 Sir Alexander Gilmour became MP for Midlothian and the Courant newspaper advertised Craigmillar for let. When Sir Alexander died in 1792 the Gilmour title became extinct.

Craigmillar Castle passed to Charles Little of Liberton and he assumed the surname Gilmour. The castle remained in the hands of the Gilmours until 1946 when a descendant of Sir John, Sir John L. Gilmour, gave the guardianship of the ruins to the Ministry of Works, later renamed the Scottish Development Department. Craigmillar Castle had ceased to be a home sometime in the late eighteenth century. The last inhabitants were two elderly daughters of Sir John Gilmour.

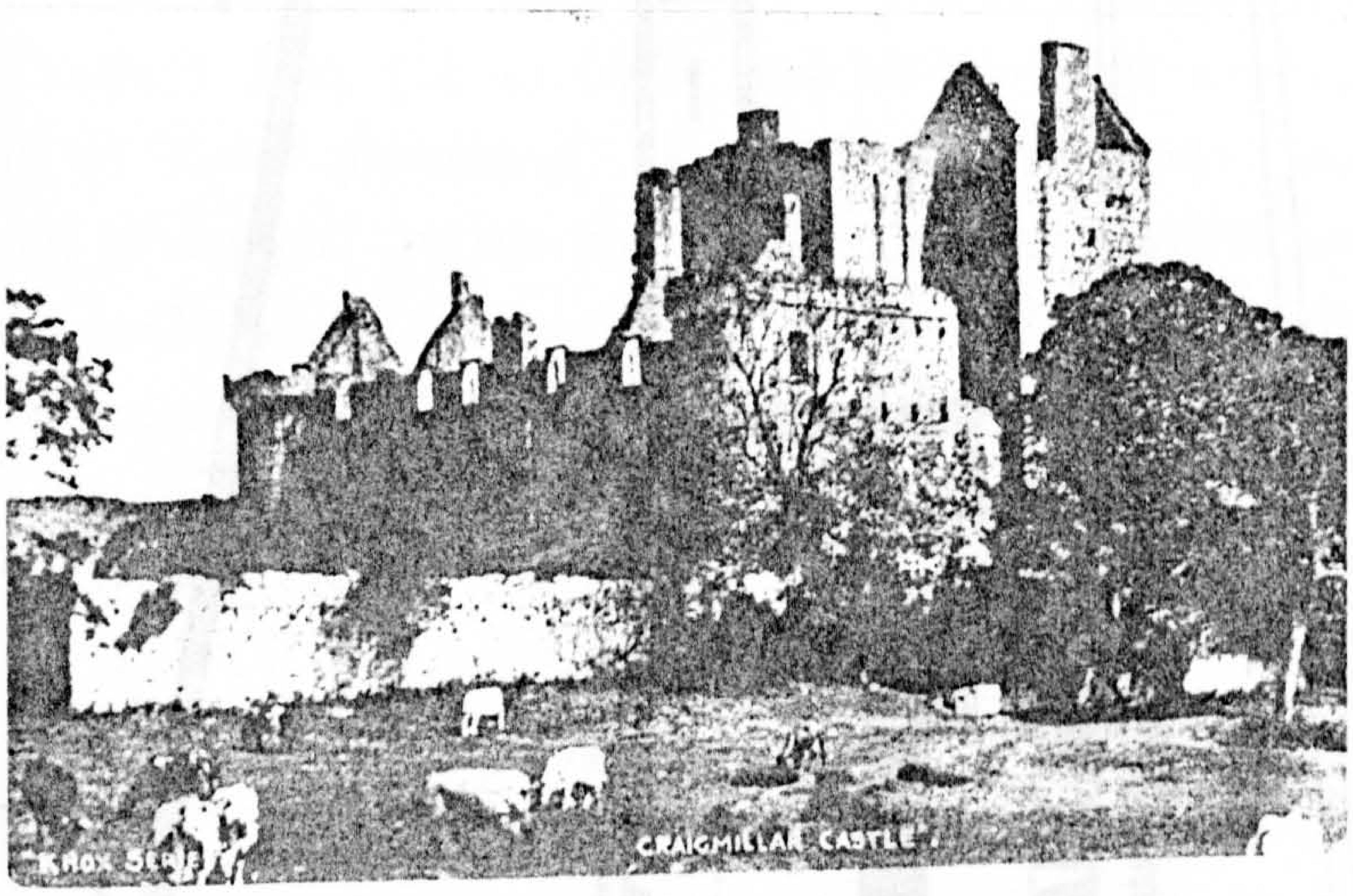


Figure 14: Craigmillar Castle (from an old postcard)

9 General plan of the castle, showing how it spread out from the nucleus of the tower house.

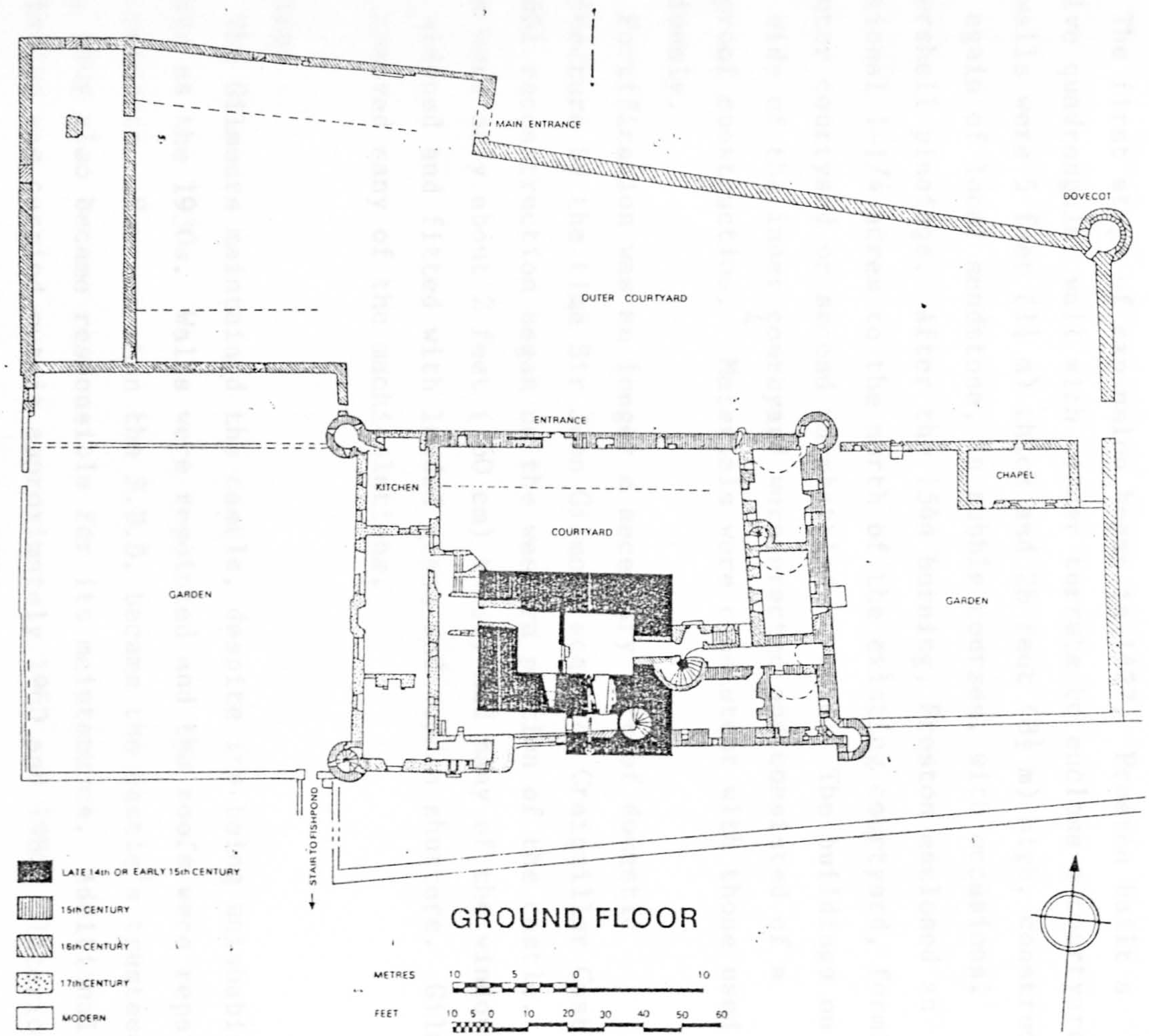


Figure 15: Craigmillar Castle
Taken from: Simpson, Craigmillar Castle (Edinburgh: Her Majesty's Stationery Office, 1980), p. 14-15.

Building Construction:

Typical of medieval houses, Craigmillar Castle was originally constructed as a fortified tower. Its defense was enhanced by its location on the edge of an abrupt cliff. Reddish-gray carboniferous sandstone, quarried locally, was used to erect 9-foot (2-2/3 m) thick, close-textured rubble walls with dressed quoins. A heavy, stone-slabbed flat roof was placed over the tower. The roof's strength and lack of pitch permitted the surface to be used for mounting military engines.

The first stage of expansion began in 1427. Preston built a massive quadrangular wall with corner turrets to enclose a courtyard. The walls were 5 feet ($1\frac{1}{2}$ m) thick and 28 feet ($8\frac{1}{2}$ m) high, constructed once again of local sandstone, in rubble courses, with occasional oystershell pinnings. After the 1544 burning, Preston enclosed an additional 1-1/4 acres to the north of the existing courtyard, forming an outer courtyard or second unembattled curtain. The buildings on the east side of the inner courtyard were erected and consisted of a fireproof construction.[4] Materials were consistent with those used previously.

Fortification was no longer a necessary part of domestic architecture by the time Sir John Gilmour acquired Craigmillar Castle. In 1661 reconstruction began on the western portion of the castle. The walls were only about 2 feet (60 cm) thick, and many of the windows were widened and fitted with leaded glass and wooden shutters. Gilmour also removed many of the machicolations.

Repairs:

The Gilmours maintained the castle, despite its being uninhabited, as late as the 1930s. Walls were repointed and the roofs were repaired with concrete. However when the S.D.D. became the castle's trustees in 1946, they also became responsible for its maintenance. Additional repointing was carried out in approximately 1960 and 1980. Interior walls were brushed with limewash in 1974.

Arden lime was used with pebbles and sharp sand in a mix ratio of 1:1:2 in the 1960 repairs. After the Arden lime quarry closed in the early 1970s, the S.D.D. adopted a bedding mix of 1:3 - 4 Portland cement:sharp sand from the River Tay. Pointing was done using hydraulic lime from Crouzilles, France and Eddleston quarry sand in a ratio of 1:2 - 3. In 1981 the western portion of the castle was being repointed, particularly the kitchen. The joints were recessed so that they are about ¼ inch (2/3 cm) from the stones' surface.

Observations:

The work, completed in the early 1960s with Arden lime, has aged very well. There are no signs of cracks or crazing; nor is there any deterioration of the joints or arrises. The same can be said for the work undertaken in 1981. It was reexamined in 1982 and based on one year of weathering, it appears as if the substitution of hydraulic lime for Arden lime has been successful, so far, in preventing cracks and other deterioration of joints and stones (Figure 16).

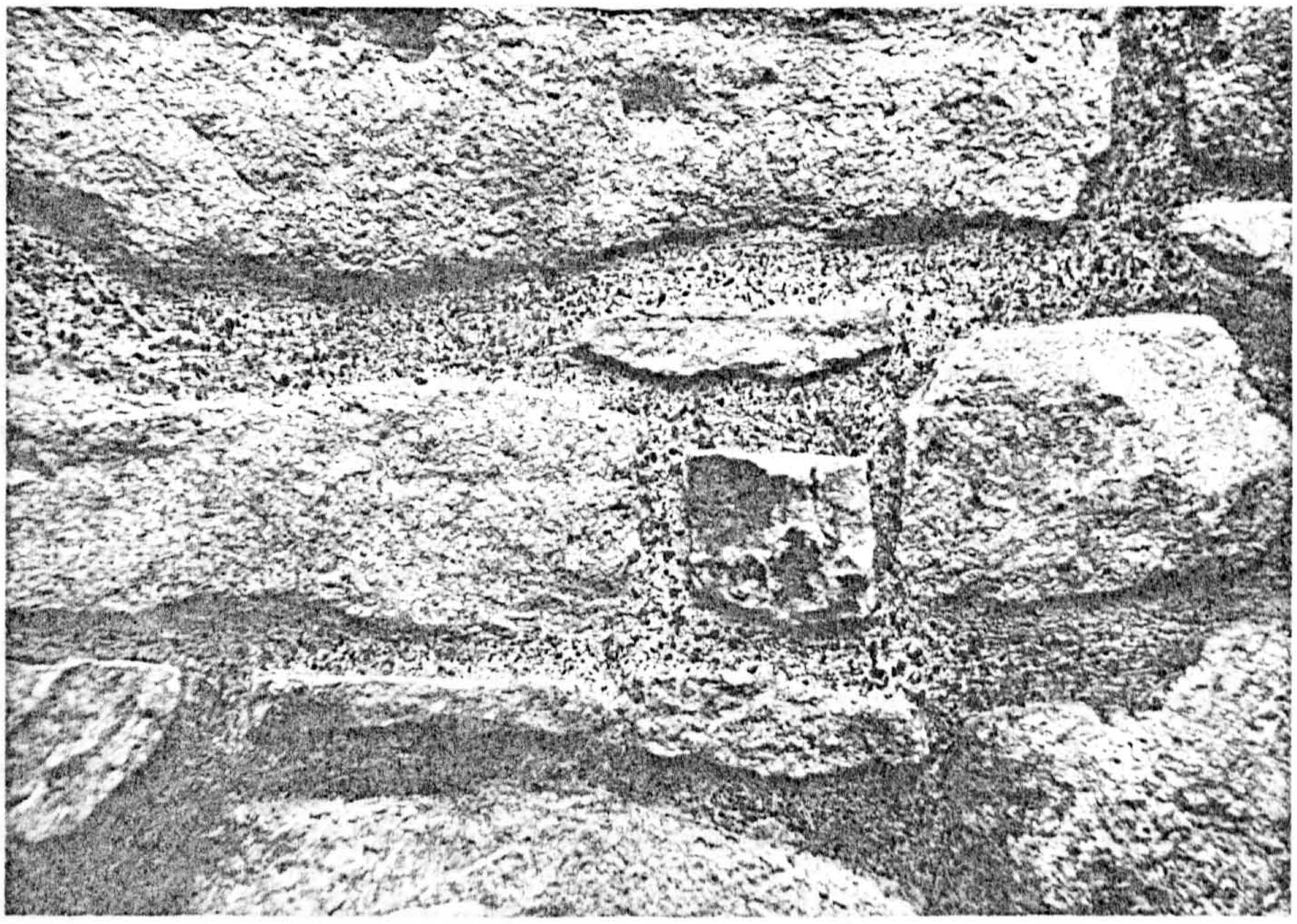


Figure 16

Fawside Castle

Historical Background:

Seven miles east of Edinburgh, Scotland, near Tranent, Fawside Castle rests on a hill that slopes down to the Firth of Forth (Figure 17). The original keep or towerhouse dates from the fifteenth century, although the Fawside family resided in the area as early as c.1150.

Aedmundo de Fazeside was the first recorded Fawside in the Edinburgh area. After Robert the Bruce led a revolt against the English, in 1307-8, 'John of the hill of Fausyde' was imprisoned in Scarborough Castle and his lands seized. The property was transfered to a family by the name of la Zouch or Souche and eventually, to William de Seton. In 1371 de Seton issued a new charter of Wester Fausyde to John of Fausyde and the lands finally returned to the Fawside family. Sometime within the next few decades the towerhouse was constructed.

In 1547 Fawside Castle was the scene for the Battle of Pinkie. The keep was set on fire and all within were 'burnt and smoothered.' The total destruction of the castle is said to have been averted 'through its first floor and roofs being arched over with stone.' Surviving Fawside members immediately set out to rebuild their home and construct an addition to the south.

Shortly after 1631 Robert Fawside sold the estate to an Edinburgh merchant, a Mr. Hamilton. By 1887 the castle was recorded as being in ruins with vegetation growing in the eaves.[5] The ruins were acquired in 1976 by T.M. Craig, and in 1978 restoration of Fawside Castle began.

Building Construction:

The original four-storey towerhouse was constructed of rubble masonry, in parts roughly coursed, using a light-colored freestone. The dressings and the quoins used a purplish freestone, and oystershell pinning was employed. The fourth storey was vaulted and the roof surrounded by a parapet walk.

After the castle was burned in 1547, a restoration followed and an

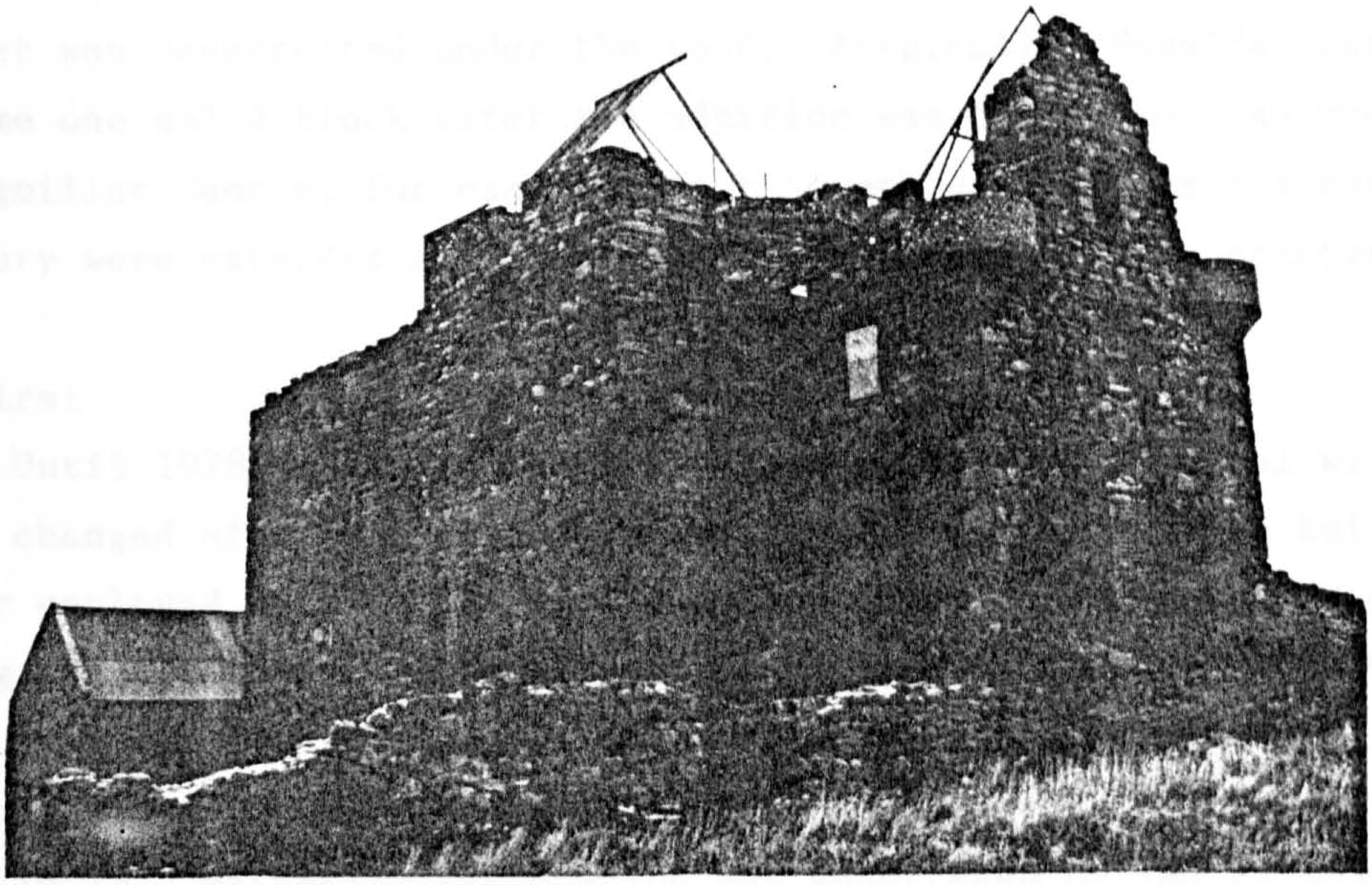


Figure 17: Fawside Castle

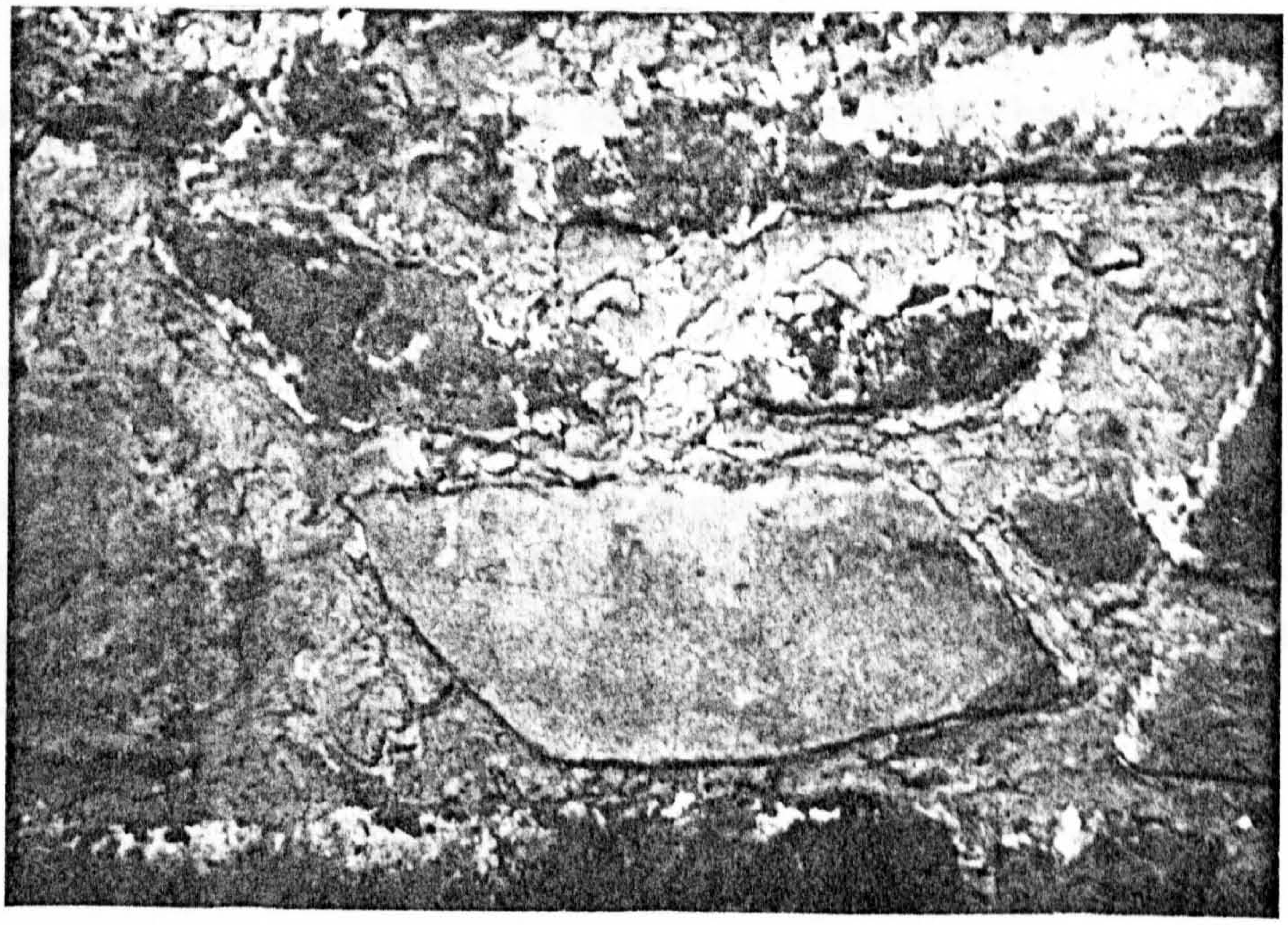


Figure 18

addition was made which doubled the size of the original keep. A gray freestone was used in the new walls, built in a random rubble. Relieving arches were placed over all windows in the addition, and a garret was constructed under the roof. Atypically, Fawside Castle became one solid block after the addition was completed. As seen at Craigmillar Castle, for example, most towerhouses of the sixteenth century were extended by adding single buildings along a courtyard wall.

Repairs:

Until 1978 alterations to the castle were few. Several windows were changed after Hamilton acquired the structure, and the building was later enclosed by a wall. Harled outbuildings were eventually erected along the periphery, although records state that one structure had the date 1618 and initials J.F.J.L. for James Fawside and his wife, Janet Lawson, carved into a dormer lintel.[6]

In 1978 extensive restoration was undertaken by Ian Parsons, architect. Walls, turrets, and windows were rebuilt and repointed. A mortar consisting of Portland cement, Tottenhoe hydrated lime, and sand was employed in a 1:6:24 mix. A ratio of 1:4 lime:sand was made, then added to the cement in a 1:6 ratio: 1 part of cement to 6 parts of the 1:4 lime:sand. The lime putty was stored in a pit for at least 24 hours prior to use. The mortar was gauged by pail and the water was added by eye. The mortar joints were pointed flush because upon completion Fawside Castle will be harled.

Observations:

As the castle was scheduled for harling, the mortar was not applied in a clean fashion. Many of the edges of the stones were covered by mortar. An inspection of the masonry in December 1983 revealed that it appeared to have aged well without visible cracks or crazing (Figure 18).

Drayton Hall, Charleston, South Carolina

Historical Background:

Drayton Hall is situated along the Ashley River near Charleston, South Carolina (Figure 19). Constructed between 1738 and 1742, it was the home of John Drayton and has become one of the leading historic and architectural buildings in the South.

Thomas Drayton, John's father, arrived in Charleston in 1679, having left Northamptonshire, England for Barbados and later, the American colonies. He settled along the Ashley River, a major transportation artery for the tidewater plantations, and built a house called Magnolia. According to primogeniture, Magnolia was left to the eldest son upon the death of Thomas. However, the youngest son, John, was given neighboring land. It was upon this neighboring land that Drayton Hall, named after the family's ancestral home in England, was built. Typical of the area, this plantation produced cash crops of indigo, rice, and cotton.

John Drayton was the first of seven generations to own the mansion. When John died during the American Revolution, the estate passed to his son, Dr. Charles Drayton. The subsequent three owners were also named Charles, the last one acquiring the Hall on the eve of the Civil War.

The Civil War ended the plantation system and with it the family fortunes. The mansion did, however, survive the Union troops due to forethought on the Draytons' part. As legend has it, they signaled to the soldiers that the house contained smallpox victims, and the house was spared. After the war Drayton Hall fell into disrepair and was occupied by squatters.

In the late 1870s phosphate deposits were discovered on the estate. The new-found wealth helped finance repairs, but in the 1880s the house once again suffered. One dependency to the main house was destroyed in the 1886 earthquake and the other was razed after a hurricane. By the mid-twentieth century the Drayton family decided to sell to ensure the estate's continuation and preservation.

The Historic Charleston Foundation joined with The National Trust for Historic Preservation in 1973 in a lease option to purchase the

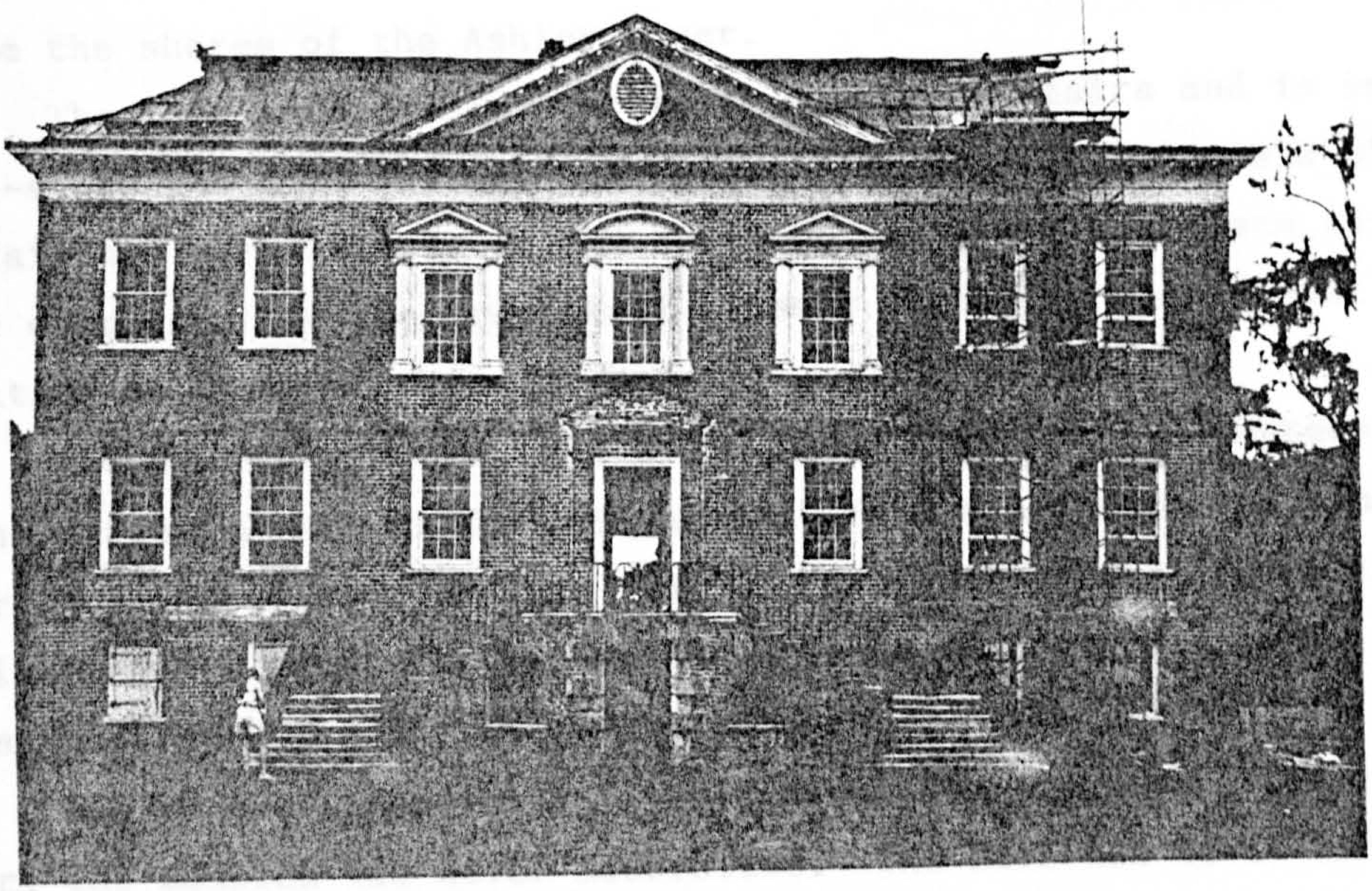


Figure 19: Drayton Hall

property from Charles H. and Frank B. Drayton. The funds were raised by 1974 and Drayton Hall passed out of the family for the first time since its construction. Today the estate operates as a historic house museum.

Building Construction:

Drayton Hall was designed in the early Georgian style by an unidentified architect. His skill, however, is apparent in the design, lay-out, and rich interiors. The red brick structure consists of two storeys over a basement. All the bricks are hand-packed, probably made on the estate during the construction period. The mortar is a traditional mix of 1 part lime and 3 parts sand, the latter obtained from the shores of the Ashley River.

The main entrance is reached by a pair of stairs and is part of a two-story recessed Palladian portico. The interiors contain elaborate detailing, particularly in the cornice, door, and fireplace surrounds. The overmantel in the Great Hall closely resembles one in Kent's 1727 edition of <u>Designs of Inigo Jones</u>.

The dependencies or unattached wings were set two degrees off a line perpendicular to the main house. From a distance the human eye corrects the offset, proving that the designer understood optical illusions. Without the offset the dependencies would appear, from a distance, to angle in toward the house.[7]

Due to the financial difficulties of the Draytons after the Civil War, the mansion was never modernized. The Hall has never had plumbing, gas lights, electricity, or central heating, and remains as such to the present day.

Repairs:

From its erection in the late 1730s until the discovery of phosphates on the estate, Drayton Hall underwent few repairs. In the late 1870s the repairs were limited to those considered important. The slate roof was replaced with galvanized tin, and the brick pediment was covered with wooden shingles. Some repointing was done in necessary areas. The mortar was pointed flush and in some areas, it slopped over onto the surrounding brick creating a wide joint of about 3/4 inch (about 2 cm).

When The National Trust acquired the estate, many areas were repaired for the first time. Repointing was a major project, encompassing the walls, chimneys, steps, and stucco work. Work commenced in the late 1970s and was largely completed by 1980.

The detailed specifications called for a different mortar for each different area:

Mortar Formulae

Formula	Where Used
1 part white Portland 4 parts lime 8 parts white sand	general use: chimneys; pointing; stucco areas around ground-level lintels
3/4 part white Portland 1/4 part gray Portland 1 part lime 3 parts limestone dust	step patches (Figure 20)
1 part white Portland 1 part lime 3 parts limestone dust	2nd formula for step patches, due to varying color of limestone dust
3/4 part white Portland 1/4 part gray Portland 1 part lime 5 parts limestone dust	lintel restoration
1 part white Portland 5 parts lime 10 parts white sand	stucco work; washes on chimneys and water table course

Epoxy was used on the step repairs to secure the stainless steel pins in place. The epoxy was made by Sika Chem in New Jersey and was called Sikadur Hi-Mod Gel.

The last mortar repairs were consistent with the original; no effort was made to remove the earlier repair mortar (Figure 21). The joints were raked out to a 1 inch ($2\frac{1}{2}$ cm) and repointed so that the new joints are recessed $\frac{1}{4}$ inch (2/3 cm), using the 1:4:8 white Portland cement:lime:white sand mix stated above. This produced a stark white mortar against the red brick, but it matched the original mortar.

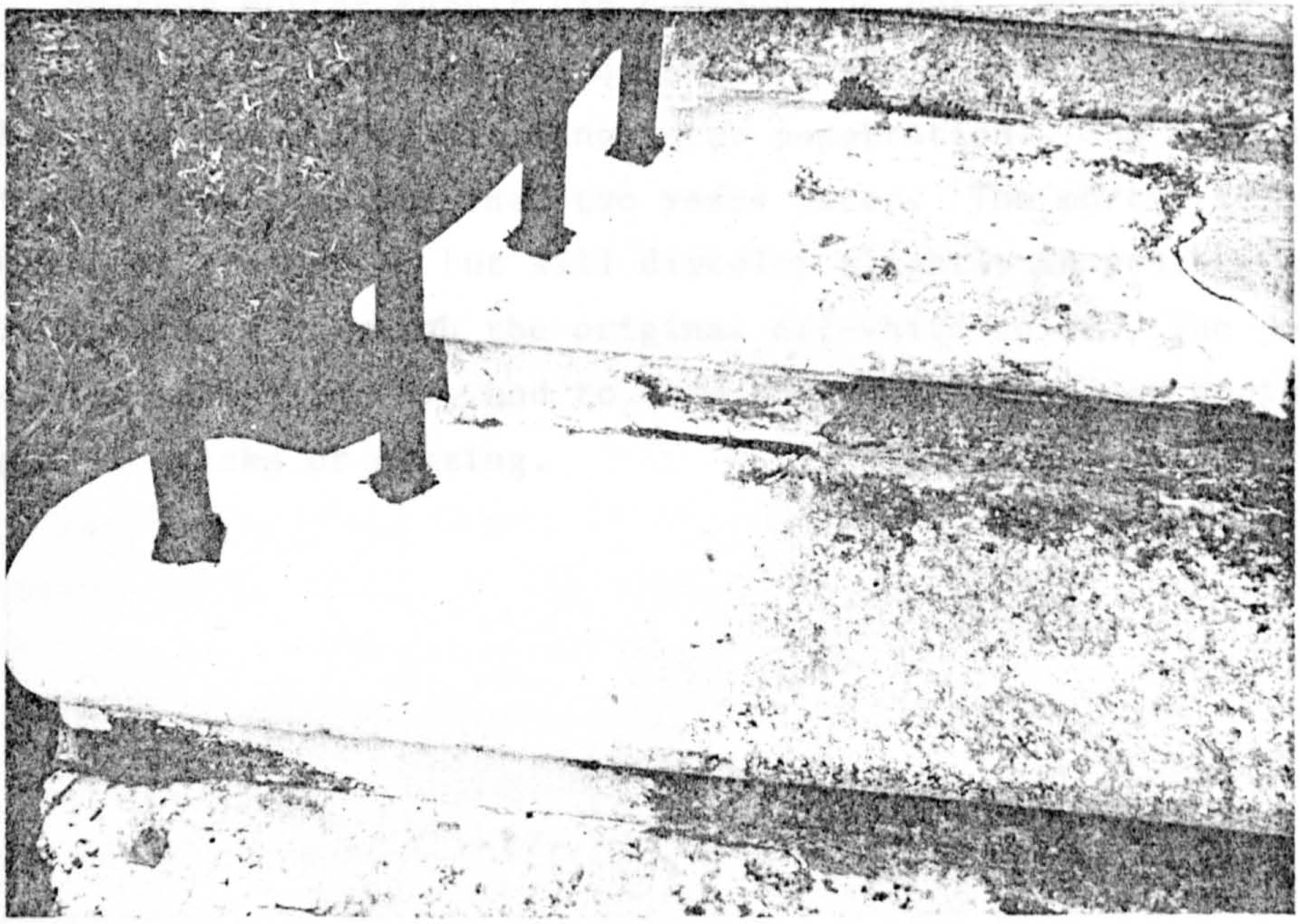


Figure 20

Figure 21

Observations:

Neither mortar repair has damaged the soft, hand-packed bricks. The first repair was merely unsightly, and in some areas it no longer adhered to the brick, allowing water penetration. The work done by The National Trust was examined two years later. The mortar is noticeable because of its color, but will discolor slightly in weathering over the next few years to match the original off-white color. The joints are indented very slightly, and to date, neither bricks nor mortar show signs of cracks or crazing.

Schermerhorn Row, Manhattan, New York

Historical Background:

The Schermerhorn Row Block, situated at the lower end of Fulton Street, is a vital park of New York City's seaport heritage (Figure 22). Located at the southeast edge of Manhattan on the East River, it was of prime importance to New York and the northeast coast between 1800 and 1860.

The Schermerhorn family first purchased land in the South Street Seaport area in 1726. At the time, that land consisted of water lots--lots which were only accessible during low tide. Between 1720 and 1800 the land beneath Schermerhorn Row was constructed of cribbing and filled with rubbish. Peter Schermerhorn (1749 - 1826) took an active interest in the neighborhood as a shipowner and merchant, and he started assembling pieces of land in 1793 until he had half a block. By 1810-12 he was constructing warehouses on this land.

In 1820 the Fulton Steamboat terminal was built near Schermerhorn Row, followed in 1822 by the Fulton Fish Market. Both these ventures helped to establish the Schermerhorn Row Block as one of the most valuable commercial holdings in the City. Unfortunately, the vitality of this area declined after the Civil War when the focus of seafaring business shifted across town to the Hudson River.

The importance of Schermerhorn Row was finally rediscovered in 1966 and plans for a maritime museum were made, and in 1968 when the block gained city Landmark status. Studies were made in the 1970s, and by 1975 a Historic Structures Report was completed, anticipating rehabilitation as a vital surviving element of the City's heritage.

Building Construction:

When Peter Schermerhorn began constructing warehouses on his block in 1811, he used the most current building methods of the time and the best materials obtainable. In 1766 New York legislation required that brick construction with slate or tile roofs be used in the built-up portions of the City. Getting enough of the proper materials was

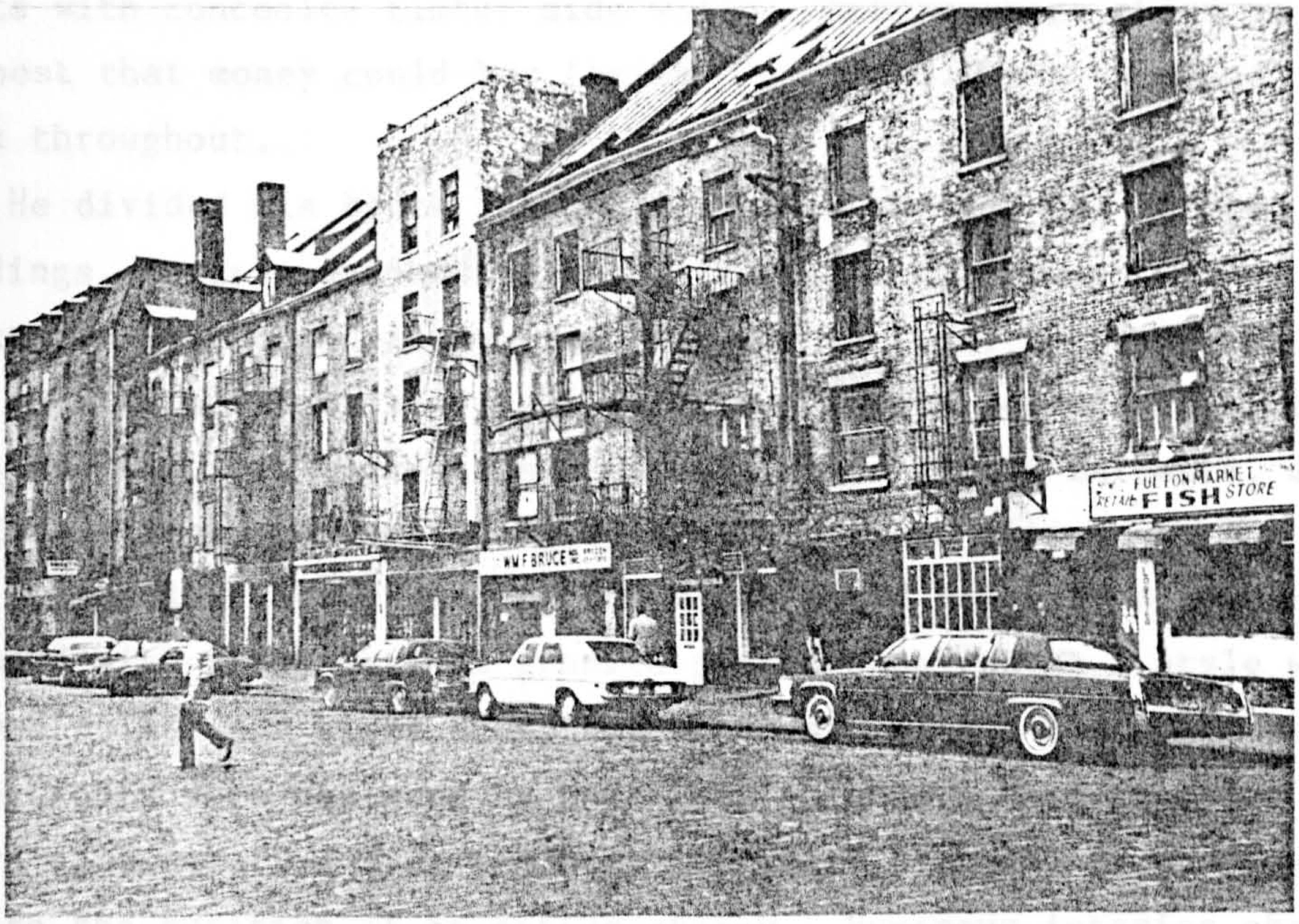


Figure 22: Schermerhorn Row

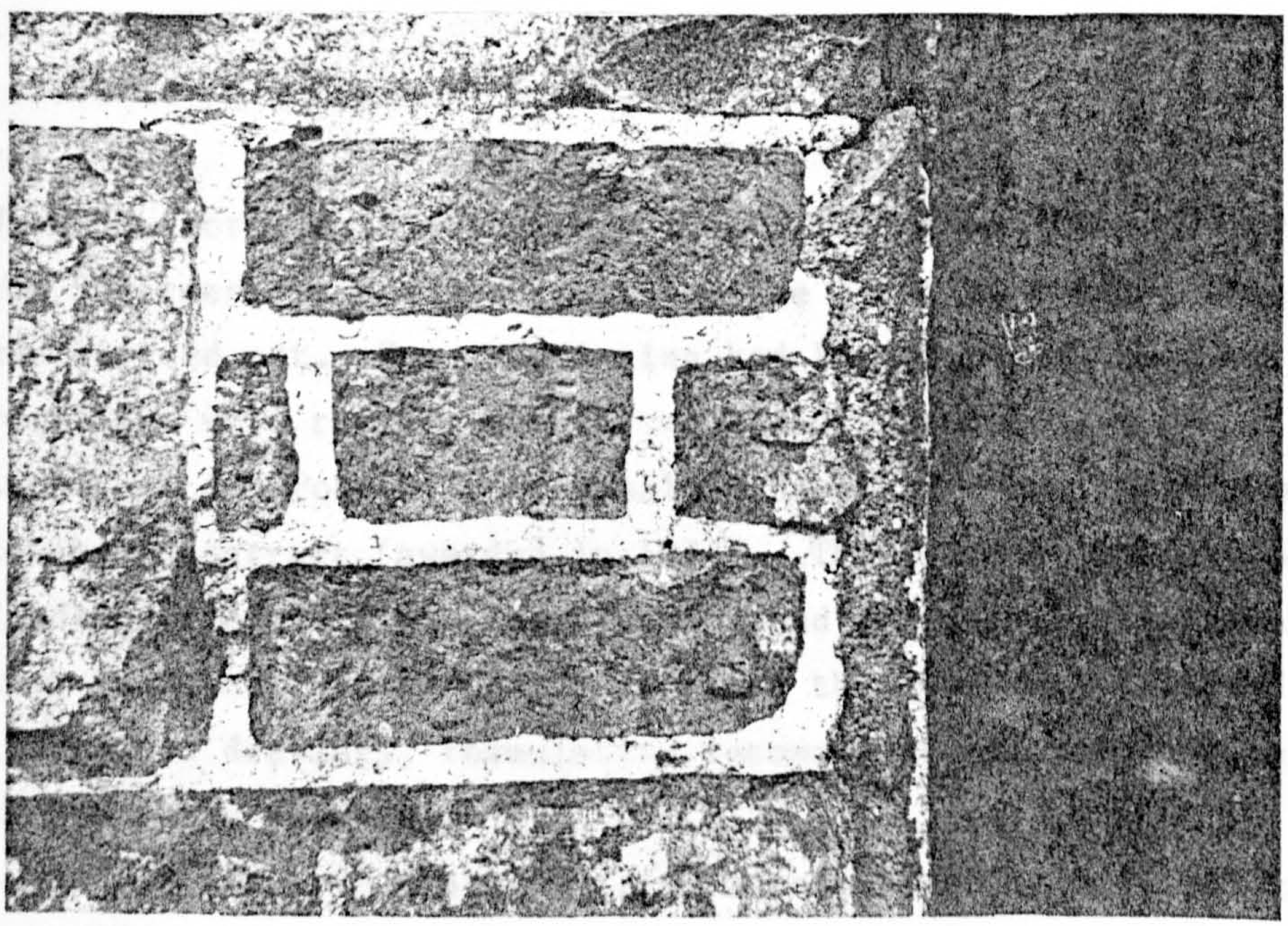


Figure 23

difficult, so builders frequently ignored the law or erected brick fronts with concealed timber side walls. Schermerhorn chose to purchase the best that money could buy (bricks costing $10 per thousand) and used brick throughout.

He divided his block into 12 irregular parcels and erected a row of buildings, largely warehouses with a few counting-houses. The structures were of an innovative "fireproof" type, typically 20 x 80 feet (6 x 24 m), four storeys high with a larged peaked attic, two bays wide, and with six-over-six sashes, an arched street entrance, and detachable iron stairs leading to a second-floor office.

By the late 1840s many of the Block's old brick fronts were replaced with Greek Revival granite piered shopfronts, a style which allowed taller and wider doors and windows. Within ten years some of these fronts were replaced by cast iron columns. Various other alterations occurred over the next 100 years, ranging from a new mansard roof to the addition of an entire storey. Numerous interior changes were made as tenants came and went.

In 1956 the neighboring structure on John and Fulton Streets was torn down for a gas station. A developer almost tore down the entire Schermerhorn Row block soon after, but could not since one owner refused to sell.

Repairs:

When New York State, Jan Pokorny, and the other firms stepped in to save the Schermerhorn Row Block, it was the first time major repair work had been carried out. Some repointing had been done in the late 1800s when rooflines were raised, but the work was sporadic.

Architect Jan Pokorny's personal involvement began in 1975 with work toward a contract (awarded in 1977). The contract called for fact-finding, restoration of the facade, and structural stabilization. The first task was to make an inventory of the building, followed by making measured drawings, formulating recommendations for work, and beginning working drawings.

A plan to create a state maritime museum/historic site caused problems and a revision in the project. The plan assumed that most tenants would move out easily, but the tenants would not. This situation made rehabilitation work more complex and difficult, and forced a redefinition of the scope of work. A new contract was awarded to revise the working drawings. Recently a five-party agreement was signed for the project, which included Rouse Associates of Quincy Market fame.

As the project was supported by state funds, a special mortar analysis was required to determine the constituents and quantities of the original mortar. This was done to enable a new mortar to be specified which would not cause any deterioration of the handmade bricks; the mortar was to be softer than the bricks. On August 17, 1979 the New York State Maritime Museum employed Norman Weiss, in connection with Columbia University, to carry out the detailed analysis.

Samples were obtained from a variety of locations on the Schermerhorn buildings and examined microscopically. Concurrently, a sand bank was compiled to allow an accurate color match to be achieved using aggregate.

Historical researchers began by studying early New York Geological Survey reports on sand and stone quarries and the sand's economic uses. Long Island, Staten Island, and the upper Hudson River deposits were known to have been used for lime mortar and brickmaking. From the color of these deposits as well as their locations, it was highly likely that the sand used in 1811 and 1868 came from one of these deposits. The fact that the 1868 sand was identical to that used in 1811 confirmed the fact that natural deposits were used rather than some of the fill used during the reclaiming of the land in 1720 - 1800.

The chemical tests concluded that the original Schermerhorn mortar was made using hydraulic lime. The sands were obtained from either beaches or rivers: the presence of small shell fragments supported this conclusion. The data indicated that in 1811 a mix of 2 parts of hydraulic lime to 1 part of sand was used.

As hydraulic lime is now not commercially available in the United States, it was necessary to simulate the physical characteristics of hydraulic lime mortars by blending lime with white Portland cement. Weiss recommended a mix ratio of 1 part of white Portland cement to 3 -

4 parts of Type S hydrated lime. To achieve a color match, 8 parts of sand was added to the above two constituents. Of those 8 parts, 2 parts was to be pink Connecticut quartz sand, 2 parts of North New Jersey brown mason's sand, and 4 parts of Long Island tan quartz sand or South New Jersey white quartz sand.[8] The joints were raked back to a 1 inch (2½ cm) depth, then repointed so that the new joints are recessed 1/8 inch (1/3 cm).

Observations:

The cooperative involvement of several historical restoration agencies has had a favorable affect on the choice of building materials used. The insistence on a detailed mortar analysis led to the use of a mortar which was weaker than the bricks to which they adhered, thus saving the old handmade bricks from irreparable harm.

Schermerhorn Row was examined in December 1982 when the repaired masonry was 1 to 1½ years old, depending on the location (Figure 23). All joints were neat and the bricks free from excess mortar. No cracks or crazing were visible in the mortar, and the soft bricks did not show any signs of deterioration caused by the mortar.

Inveraray Jails

Historical Background:

The New Town of Inveraray in Argyll, Scotland is situated on land which juts out slightly into Loch Fyne. Proposals for a new town were made in 1756, within sight of Inveraray Castle, the home of the Duke of Argyll. Considerable work was carried out in the last half of the eighteenth century by the architects, Robert Mylne (1734-1811) and John Adam (1721-1792). The latter erected the county courthouse and jails on Front Street, facing the harbor.

The nineteenth century, however, brought with it an increased interest in comfort and hygiene, and the first to be pronounced unsuitable were the jails. Inverarary citizens felt that Adam's design had sacrificed convenience and usefulness for appearance.[9] The building had three large doors which opened into a piazza onto which the jail cells faced. Prisoners were allowed to exercise in the piazza, and as such, all passersby had a full view of the 'miserable appearance' of the inmates and their squalid conditions, not to mention easy access to converse with the prisoners.[10] In addition, it was the first building people saw when they entered the town.

Complaints continued for several years, but lack of money prevented immediate reform. Finally in 1807 the County Commissioners of Supply invited proposals for additions or new construction on a new site. Plans submitted by Robert Reid of Edinburgh were approved by the Commissioners, but at each meeting they fell short of a quorum. Also, the county lacked the £7,000 required to build Reid's design.

New plans were requested and James Gillespie visited Inveraray with his ideas. He immediately abandoned the idea of extending the existing jail, and proposed a more remote site on the other side of town where it was drier, healthier, and more secure. The cost in Gillespie's estimation would be £5,712.

The courthouse and new jail were completed by 1820 at a cost of £6,197.2s. In 1843 another jail was erected to separate the men from the women. Both jails were situated between the rear of the courthouse and an approximately 10-foot (3 m) high wall. Beyond the wall the land

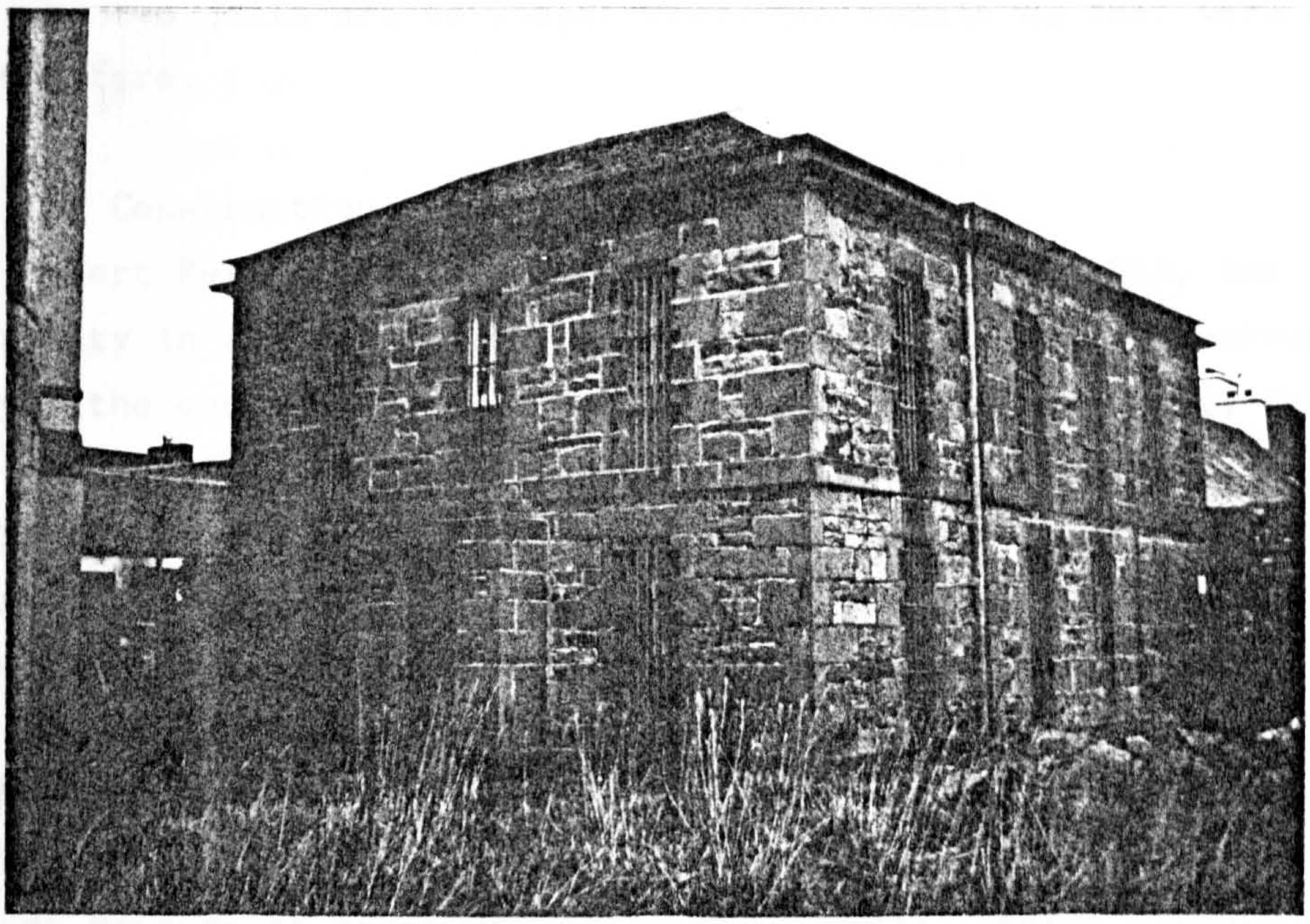


Figure 24: Inveraray Jail for Men

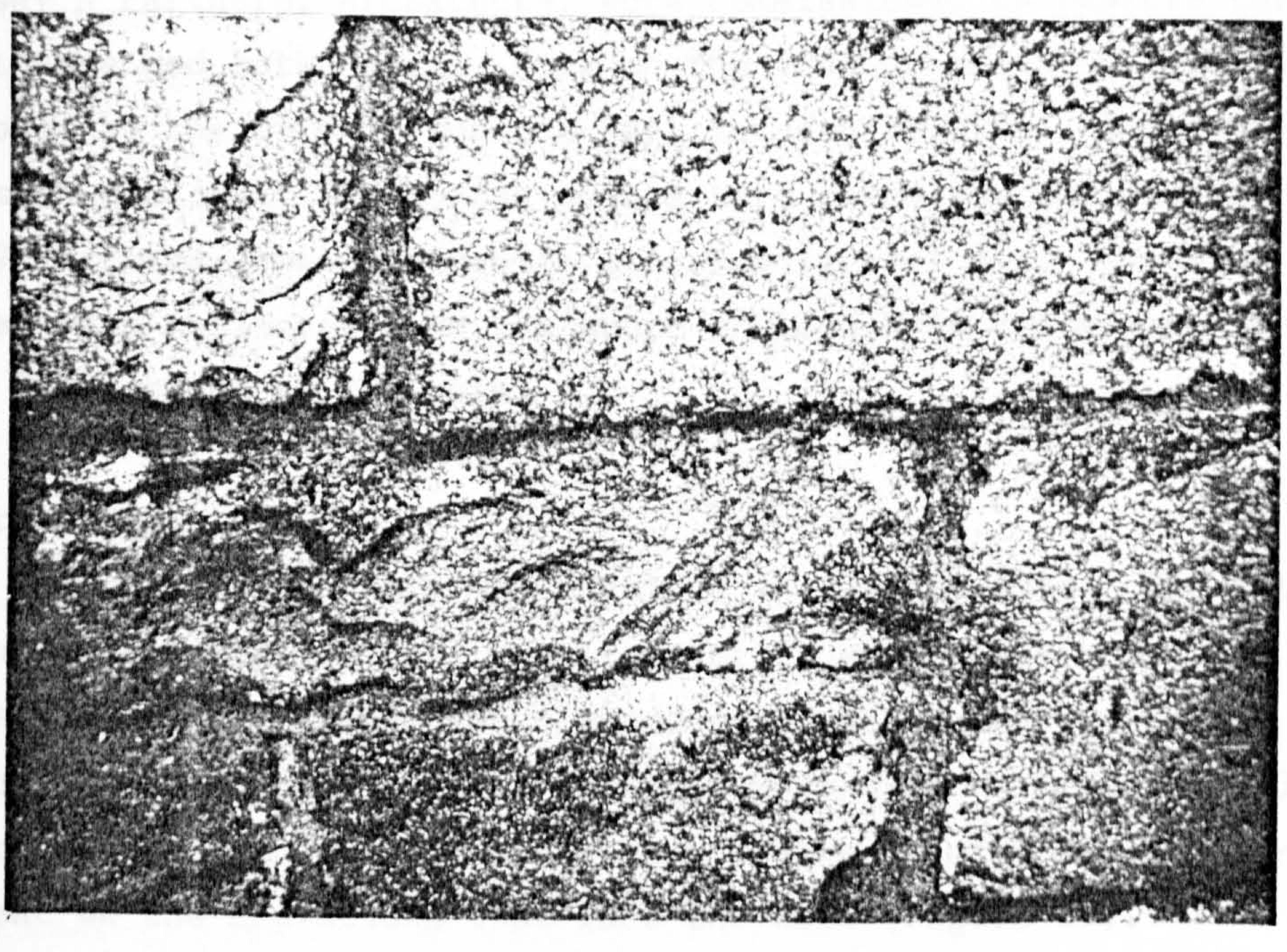


Figure 25

drops to the shore of Loch Fyne.

The two jails are no longer used, but remain as they were over 100 years before.

Building Construction and Repairs:

Robert Reid's plan was modified by Gillespie by 1813, but difficulty in obtaining final approval and the necessary contractors delayed the construction date of the new courthouse and jail for three more years. Finally in 1816 the builders, William Lumsden and James Peddie, of 13 Charlotte Street, Leith, were signed to a four-year contract for £5,850.2s.[11] The courthouse and jail were completed, after further delays, in 1820, upon which Peddie declared bankruptcy.

The two-story jail was constructed of dark red granite with 3-foot thick walls, in contrast to the light-colored stucco of the back of the courthouse (Figure 24). The walls were of "strong coursed rubble...with rows of Headers at every 2nd course."[12] Large, grated windows covered each facade, allowing the prisoners plenty of sunlight and fresh air. In 1843 a similar, second jail was erected just across the courtyard.

The jails existed with few repairs until 1980. In April, Ian Lindsay & Partners, Architects, were commissioned to restore the courthouse and both jails. Work on the 1843 or men's jail began first, followed by the 1820 or women's jail in January 1981. Repointing was the main concern. The mortar joints were raked out and repointed with a 1:2:9 Portland cement:hydraulic lime:sand/gravel mix. The sand and gravel were collected from the shore of Loch Fyne and washed free of salt by exposure to the rain.

Observations:

The restoration work was examined in January 1983. The joints are slightly recessed from the granite, but in some areas are flush with the stone. All joints have been cleaned such that no mortar covers the stones' arrises. The masonry has aged well over the ensuing 2-3 years. No crazing or cracks are visible, but traces of efflorescence are present on the elevations that face the Loch (Figure 25).

Thirlestane Castle

Historical Background:

Just north of Lauder, Scotland, Thirlestane Castle stands on the banks of the River Leader, surrounded by parklands. Dating from the late 1500s, the castle served as the residence of the Maitland family since the twelfth century.

The Maitlands of Lethington and Lauderdale descend from an Anglo-Norman family that settled in Berwick during the reign of William the Lyon. Throughout the centuries they have served the Scottish Crown, often in the position of Secretary of State or Lord High Keeper of the Great Seal of Scotland. The first of considerable note was Sir Richard de Matulant. He was a powerful baron in Scotland during the reign of Alexander III (1241 -1286), and he defended his home against English invaders. His son, William of Thirlestane, was a follower of Robert the Bruce. A Maitland of Lethington fell at the Battle of Neville's Cross in 1346. Another was a close friend of James IV and died with him on the field of Flodden in 1513.

With such positions as the Maitlands held, their castle became a important stronghold and military center. It was captured several times by the English, and in 1548 the 'enemy' even strengthened it to hold an English garrison. After the lands were returned the current castle was begun in 1570 by Chancellor Maitland (1545 - 1595). Additions were made in 1660 by the first and only Duke of Lauderdale, John Maitland (1616 - 1682). Thirlestane Castle remains in the Maitland family and is now owned by Captain The Honorable Gerald Maitland-Carew, grandson of the 15th Earl of Lauderdale.

Building Construction:

Thirlestane Castle, as it is known today, was constructed in 1570 on the foundations of an old fort, itself dating from 1350. Typical of its time, the towerhouse was oblong in plan with small windows and gunloops. Circular towers and turrets were built at the corners, each supported by corbels. The walls were of small rubble masonry and were three storeys high with an attic (Figure 26).

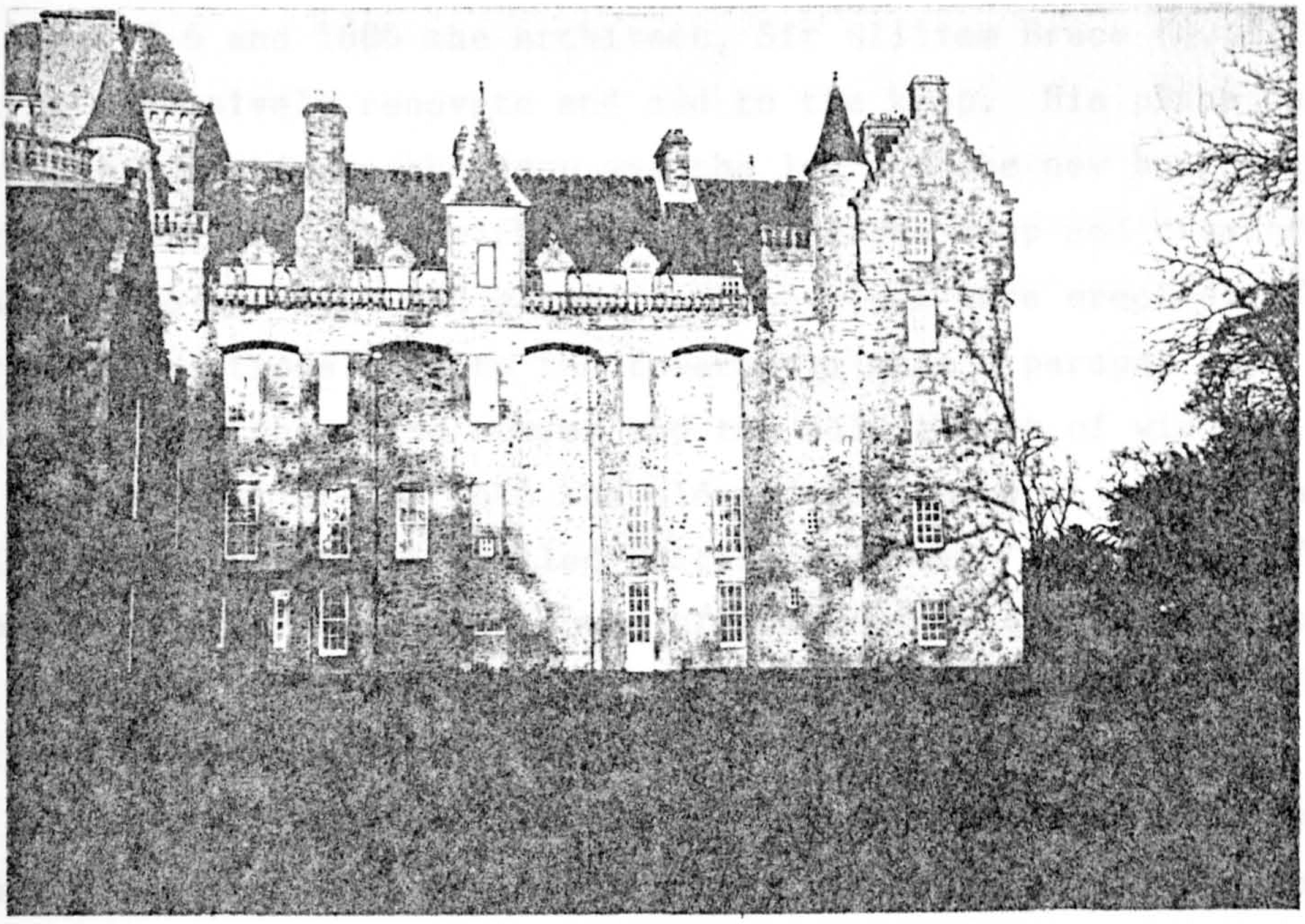


Figure 26: Thirlestane Castle

Figure 27

In 1670-6 and 1680 the architect, Sir William Bruce (d. 1710), was hired to extensively renovate and add to the keep. His plans called for a T-shaped formation: the keep was the leg and the new buildings formed the cross-bar. Bruce took the west wall of the keep and created a new entrance. To the left and right, jutting wings were erected. The only external alterations made to the towerhouse were a parapet walk installed above the third storey and the enlargement of windows.

On the interiors of both the old and the new portions of the castle, Bruce brought in skilled British and Dutch craftsmen. These workers carved garlands and crowns of the Restoration in wood and plaster on the walls and ceilings. A mansion was created out of a fortified towerhouse.

In the nineteenth century the last of the additions were made. Further extensions were constructed onto the Bruce wings, and dormers and square turrets were added to the original castle.

Repairs:

In April 1980 Ian Lindsay and Partners, Architects, were commissioned to repoint the rubble walls of the towerhouse. The joints were raked out and repointed flush with a 0:1:3 mix ratio of hydraulic lime from France:well-graded sand from the isle of Iona, Scotland. The mortar was tamped in with a soft brush and then sponged. This mix proved to have a high shrinkage rate, and within a short time tremendous contracting and cracking were noted.[13]

Lindsay and Partners returned, raked out the new mortar, and replaced it with a 1:2:9 Portland cement:French hydraulic lime:Iona sand mix. Again it was applied with a brush and sponged. The joints of the rubble walls were pointed flush.

As the walls were constructed of random rubble, the mortar joints varied in size. Typically they were 1 inch (2½ cm) wide, but some areas had joints up to 2 inches (5 cm) wide. The placement of the stones dictated the width of the mortar joints.

Observations:

The restoration work was examined in November 1982. As the mortar was flush with the stones, there were many areas where the arrises were covered by the mortar. Despite this condition, there is no evidence of spalling or damage to the stone. The masonry has aged well with no deterioration, except for some vertical crazing (Figure 27). This is largely apparent around openings or where the new mortar abutts the old and is caused by shrinkage.

Hermits and Termits

Historical Background:

By 1731 St. Leonard's had become a small village on the outskirts of Edinburgh. The southern most row of houses in the village was owned by a Mr. Clifton and the two southern most houses in that row were called Hermits & Termits. The name derived from two crofts built in the area in 1494.[14] The units were typical of the area, and one had a plaque over the door dated 1734 and displaying the crest of a William Clifton.

Clifton lived there for five years, and upon his death the house passed to his son. Between 1739 and 1782 when the son died the house and surrounding land was sold in pieces. At the same time most of the village was being absorbed or lost by expansion and industrialization. The row of houses disappeared and when, in 1780, Captain Thomas Bridges purchased the Clifton house, it was surrounded by a large 2-acre garden. Consisting of four main apartments, the house was by then known as Hermits St. Termits.

In 1807 the house was leased to Robert Scott, father of David and William Bell Scott. In 1828 Bridges's widow sold the land to the Edinburgh & Dalkeith Railway Co., who built a railroad terminus there for the dispersal of coal from the Niddrie & Musselburgh collieries. The house served as the offices for the coal yard and, later, was the home of the coal yard caretaker. The caretaker lived there until his death in 1968.

Hermits and Termits lay vacant for nearly 10 years, until Benjamin Tindall purchased it for his residence and office (Figure 28).

Building Construction and Repairs:

From the plaque that still exists over the door, it is assumed that the house was constructed in 1734 by William Clifton. The walls consisted of rubble sandstone with pink sandstone surrounds and quoins. They were then harled. From an analysis made of the original harling, it was surmised that the mix consisted of 2:1 lime:sand with large pebbles.[15] The interior was constructed of timber and one

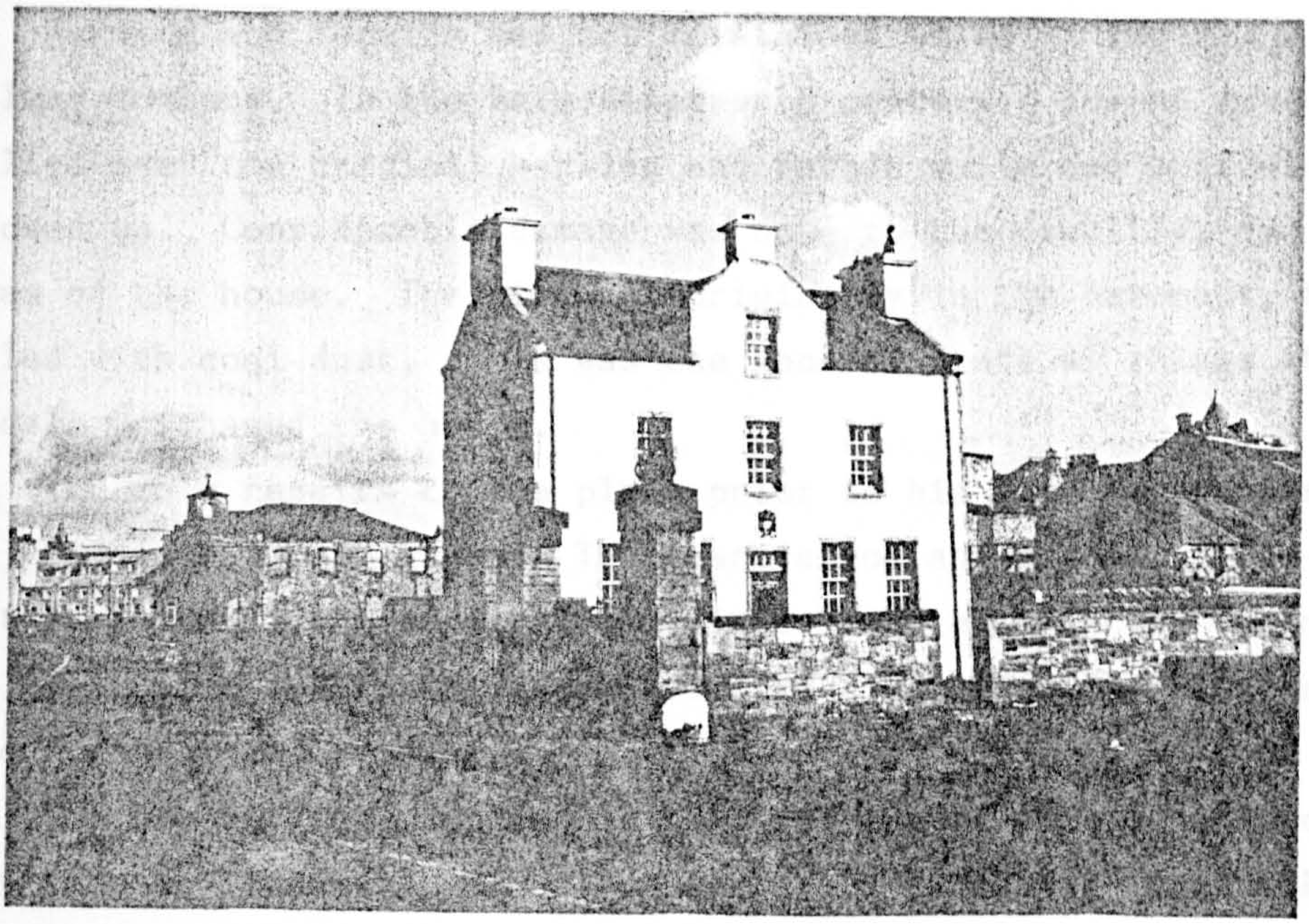


Figure 28: Hermits and Termits

Figure 29

ground-floor room had panelled walls of tongue and groove.

Hermits and Termits was not maintained while it was owned by the railway company. In the late nineteenth century a cement render was applied over the original harling and rubble walls and most windows were bricked up. Considerable damage was done to the panelling and other areas of the house. The kitchen, originally in the basement, became filled with coal dust. This was the general state of things when Tindall purchased the house.

The sole repairs to the place prior to his purchase consisted of the render mentioned above. The restoration and massive clean-up were left to Tindall, who repaired the windows and emptied the basement of its dust. The rubble walls were pointed flush with the stone after the cement render was removed.

The new harling, applied in July and August 1981, consisted of one coat and one limewash. The first was a 1:2:9 Portland cement:hydrated lime:fine sand, followed by a mix composed of 1 bag of quicklime, 1 can of vegetable oil, water, and a 1:3 mix of ochre and white pigments. The first coat was allowed to dry to insure that no cracks or crazing appeared. Then the quicklime and oil were combined and made into a slurry with water. The pale yellow color created from the 1:3 pigment mix was added. This limewash was brushed onto the first render and any spillage on the pink sandstone was removed (Figure 29).

Observations:

When the building was examined in 1983, two years after the limewash was applied, no cracks, crazing, or other damage was apparent.

Buccleuch Church Wall

Historical Background:

Buccleuch Parish Church is situated on the south side of Edinburgh on Buccleuch Street. Now it is surrounded by tenements and University of Edinburgh buildings, but when it was erected in 1755 it was probably considered to be 'just outside of town.'

The church was originally built as a annex to the West Kirk or St. Cuthbert's Church located in the West End, and was named the 'Little Kirk' or 'Chapel of Ease.' The doors opened to 1,200 parishioners in January 1756. By 1763 its adjoining land, having been enclosed, was made available for interments.

The south side of Edinburgh grew rapidly in the following decades, limiting the expansion of the cemetery. The chapel and its abutting lands became defined by Buccleuch Street on the east, Windmill Street on the north, Windmill Lane on the west, and the tenements facing Buccleuch Place on the south. Finally on November 27, 1820 the graveyard was closed to all save those who had already purchased a plot.

On May 31, 1834 the Chapel of Ease broke away from St. Cuthbert's and became known as Buccleuch Parish Church. It has retained its size and name to the present day, but in 1866 the structure received a new facade.

Building Construction and Repairs:

The Chapel of Ease was erected in 1755 at a cost of £642. A 10-foot (3 m) high, rubble masonry wall was constructed to enclose the chapel and its lands, broken only in front of the chapel by iron gates. By June 24, 1767 a resident of Edinburgh observed that the wall had become very irregular.[16] Nothing more was mentioned until grave robbing became a problem in the early 1800s. In 1829 the gates were removed in favor of doors to deter robbers as this graveyard lacked a watchtower. By 1866, however, the doors had again been replaced by iron railings and gates which have been used ever since.

Periodically the 10-foot wall has been repointed, although records do not mention when. Finally, in July 1981, repairs were made to the

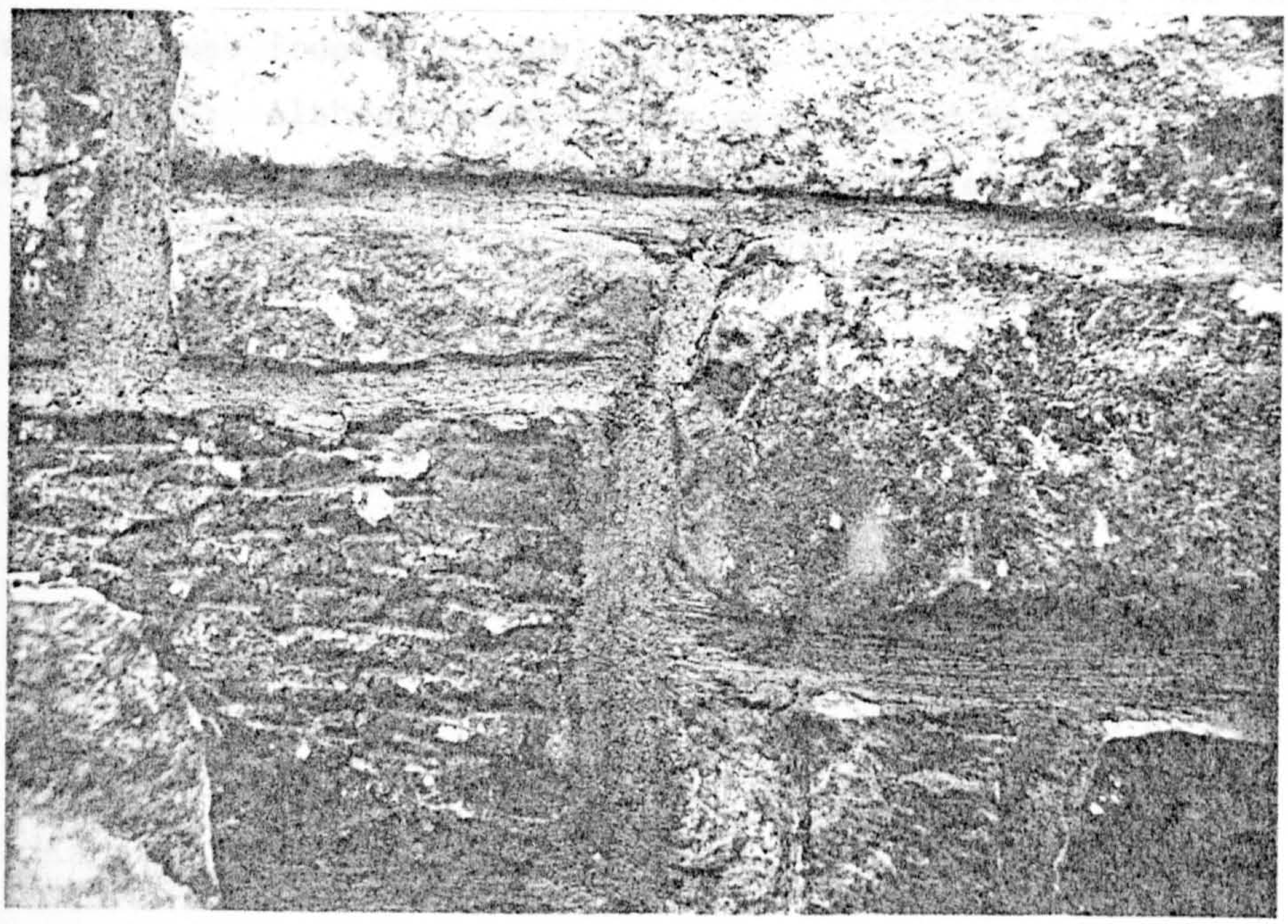


Figure 30: Buccleuch Church Wall

Buccleuch Street wall under a contract to Orbit Builders. Orbit examined the old mortar and to provide a similar consistency, decided on a mix ratio of 1:2:4:4 Portland cement:hydraulic lime:concrete sand:builders' sand. The mason included concrete sand as it "shines the smaller stones" in mixing and weathering to achieve a greater match with the older mortar.[17] The mortar was pointed so that the new joints are recessed about ¼ inch (2/3 cm) from the stones' surface.

Observations:

The 1981 repairs were examined in 1983 (Figure 30). At that time the masonry was free of cracks, crazing, and other forms of deterioration. Although some mortar was allowed to remain on the arrises, no spalling of these corners had occurred by 1983.

Mylne's Court

Historical Background:

Surrounded by protective walls, the burgh or city of Edinburgh originally developed along a single main street running from the gates of the castle to a gateway situated at the the opposite end. The axial street, known as the High Street or the Royal Mile, served as a thoroughfare and marketplace, was lined with buildings, and had closes or smaller streets connected to it.

Until approximately 1630 buildings tended to be constructed of timber and thatch. Afterwards stone structures were erected, several storeys in height. As shortages of living space occurred, taller tenements were built. One typical tenement, reached by a close entering into a courtyard off the Royal Mile, was Mylne's Court (Figure 31).

It served as a tenement until it was vacated early in the twentieth century, due to the lack of modernization and the bad state of repair. The standards of accommodation varied with upper flats being reached by a side door. The main entrance led to the home of an Edinburgh merchant.

In the 1960s the University of Edinburgh purchased it for conversion into graduate halls of residence, namely Salvesen Hall and Philip Henman Hall.

Building Construction and Repairs:

Constructed between 1730 and 1760 Mylne's Court, upon completion, was the tallest tenement in Scotland. It was five storeys high plus a dormered attic and was seven bays wide on the front facade. The walls were of random rubble with sandstone quoins.

The main door facing the courtyard led to the merchant's house. Much of the detailing was lost in subsequent centuries, but one room still retains the wood panelling complete with pilasters and other similar designs, the fireplace and the inset cupboard.

When the University acquired the tenement, considerable restoration work was required. The masonry needed repointing. On the interior, timber floors were sagging and stabilization was necessary before

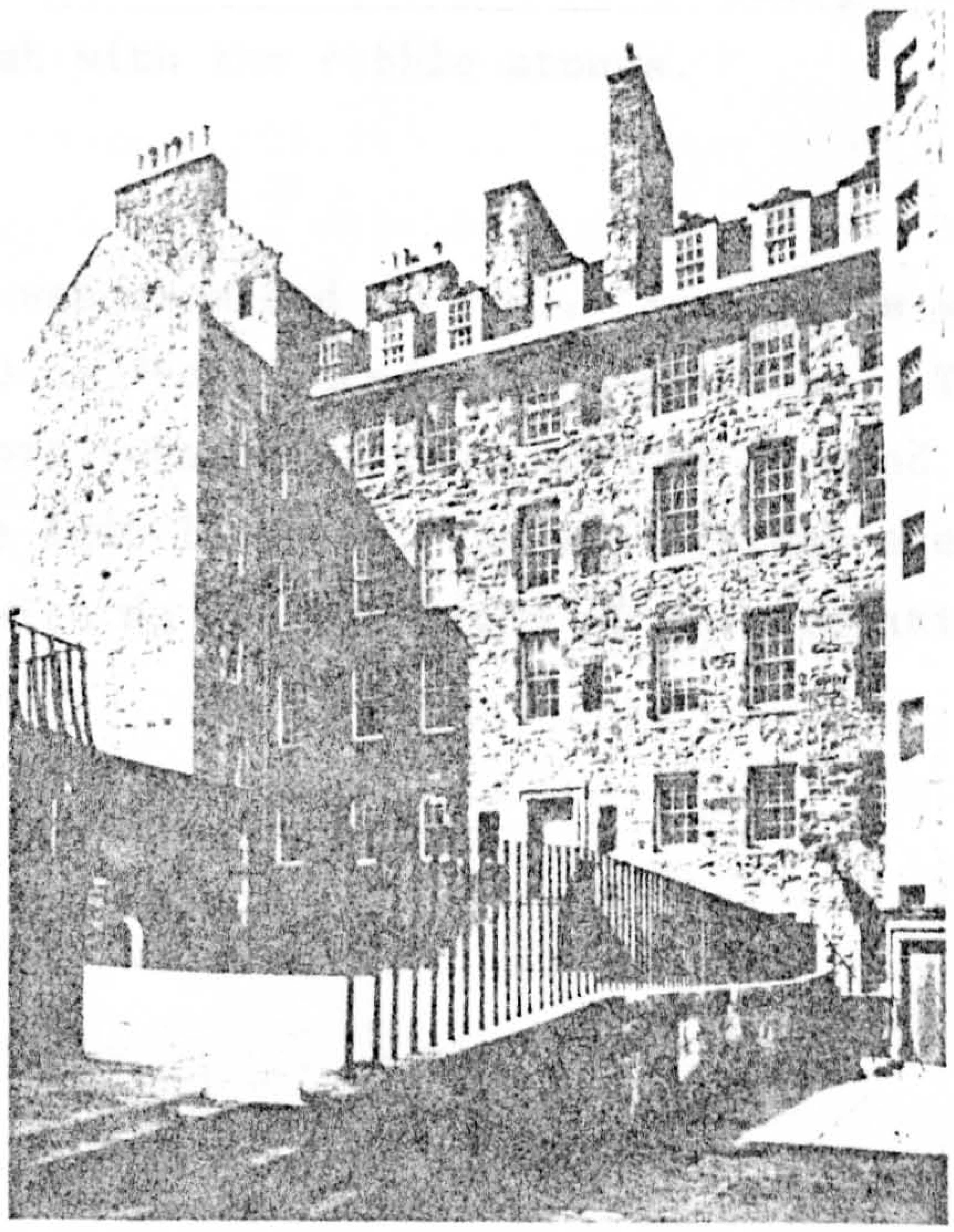


Figure 31: Mylne's Court

Taken from: Stewart, The Past Hundred Years: The Buildings of The University of Edinburgh (Edinburgh: University of Edinburgh, 1973), 19.

conversion could begin. Ian Lindsay & Partners, Architects, and T. Harley Haddow & Partners, Engineers, were hired and restoration began in 1965. The project was completed in 1970.

In repointing the structure, a mortar mix of 1:1:6 Portland cement:hydrated lime:sand was used. The engineering firm requested this mix as it was one of three standard mixes on which stress figures were readily available. Having used the mix before, the firm could anticipate how the mortar would weather.[18] The joints were filled just short of flush with the rubble stones.

Observations:

The building was examined in 1983. Rear walls were not accessible; only the courtyard or front facades were examined. The front faces south, and therefore, weathers less than the exposed northerly walls. However during the last 13 years, the masonry has aged well. All the joints are tight with no visible signs of deterioration.

The Public Theatre, Manhattan, New York

Historical Background:

Located in lower Manhattan amid what was once an industrial area, the Public Theatre was originally constructed in 1853 as the Astor Library for the poor and working classes (Figure 32). It was financed by John Jacob Astor (1763 - 1848) and was his only public benefaction. Situated at 425 Lafayette Square, it was the first library in the United States to be made available to the public.

Astor specified that his library be open from 10 a.m. to 4 p.m. and that the books remain in the reading room. These regulations defeated the purpose of the libary as most of the working class could not visit during the open hours. As a result, the library moved to Bryant Park in 1911 to attract more people with time on their hands. The Astor Library merged with the Lenox Library and the Tilden Trust to form the New York Public Library.

Following the 1911 move, the Lafayette building became the home of the Hebrew Immigrant Aid Society. The Society was established during the great influx of immigrants from Eastern Europe to provide shelter, jobs, and other forms of aid. By 1965 the structure had outlived its usefulness to the Society and was placed on the market for $550,000. Just as a sale contract was being drawn up in September 1965, the recently-formed New York Landmarks Preservation Committee designated the building a Landmark. Protests were made by the Society that this action would inhibit the sale.

Concurrently, Joseph Papp, director of the Shakespeare Festival Public Theatre, contacted the Landmarks Commission and asked if they knew of a Landmark for sale. The Theatre had been giving free performances outdoors in Central Park, but now wished to move indoors. Papp was told to contact the Hebrew Society immediately as the potential purchaser for the old Astor Library wanted to demolish it. Papp found the $550,000 with the aid of contributions, saved the building, and converted it into a theatre. He even persuaded the man who had planned to tear it down to donate money. The structure became The Public Theatre.

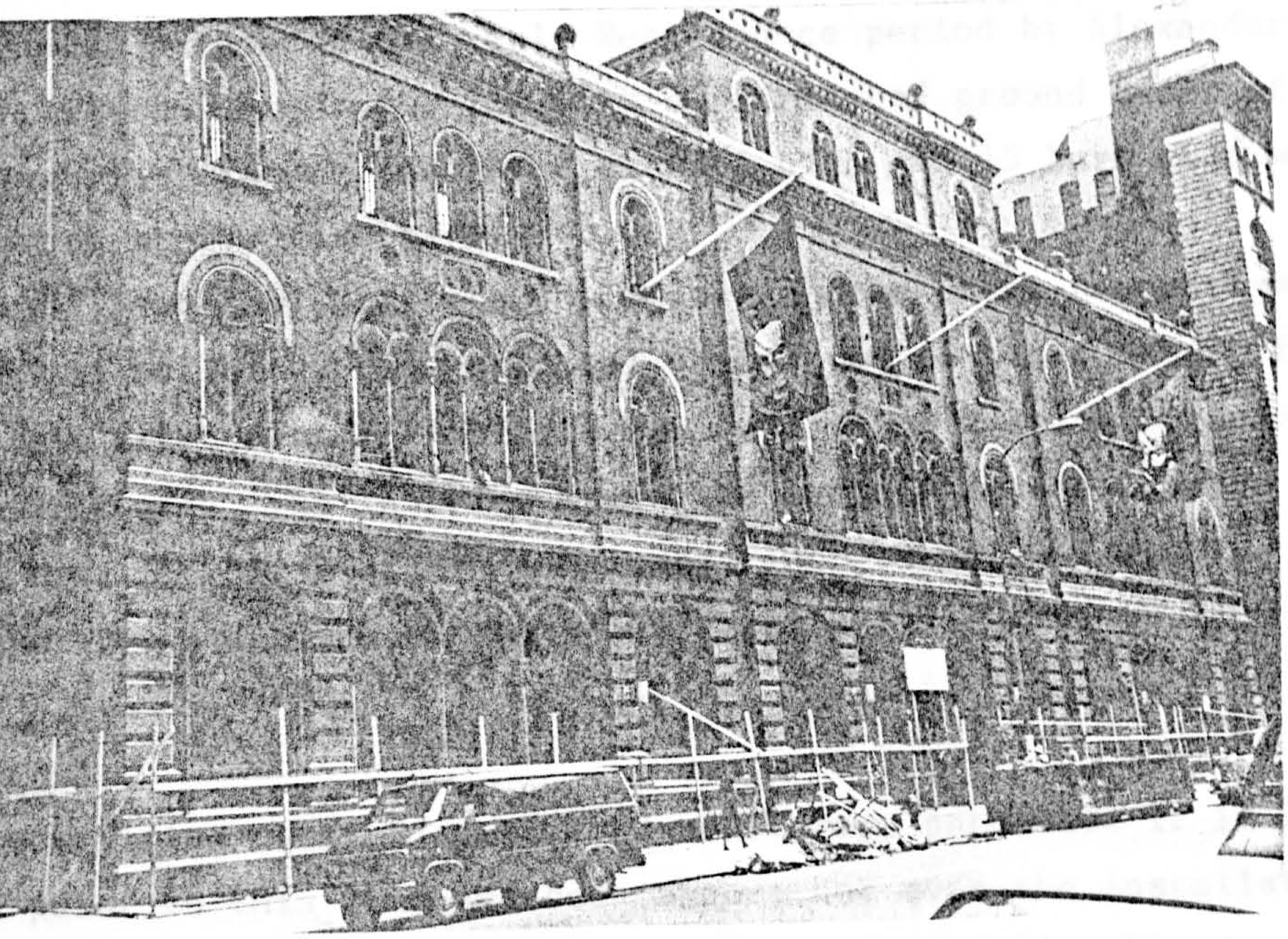


Figure 32: The Public Theatre

Figure 33

Building Construction:

Construction of the Astor Library began in 1853. Designed as a north-Italian palace of the early Renaissance period by Alexander Saeltzer, it consisted of brick with a rusticated ground floor of sandstone. The library was three storeys high and 15 bays wide with a small fourth storey five bays wide.

In 1859 and 1881 Griffith Thomas and Thomas Stent respectively extended the building. The original design was so meticulously followed that it was extremely difficult to tell where one section began and another left off. The interior space was largely devoted to the reading room, a room lit by skylights and large floor-to-wall windows at one end with balconies and books on the other three walls.

Repairs:

The building remained unaltered until Papp purchased it in 1965. Repairs prior to this time had been minor; not even the installation of subways below the library in 1904 and 1917 caused noticeable damage. The mortar and masonry were strong--although the exact mortar mix used in the construction is unknown. Some repointing occurred at an earlier date and was applied in such a fashion that all pits in the bricks were also filled with mortar (Figure 33).

Papp hired New York architect, Giorgio Cavaglieri, to do the conversion. With the exception of repointing, the exterior remained unaltered. The majority of the work occurred inside. Gone was the elegant reading room and in its place were a series of dramatically modern stages for various types of productions and the necessary subsidiary rooms for dressing, prop storage, etc.

The Cavaglieri specifications for the repointing of the brickwork were extensive. Under the heading, Materials, they read as follows:

1. Water shall be clean and fit to drink.
2. Cement shall be standard brand of Portland cement of American manufacture which meets the minimum requirements of the ASTM.
3. Fine aggregate shall be sand, graded from fine to coarse and free from injurious amounts of clay or other impurities. At least 95% shall pass a No. 4 sieve. Not more than 30% nor less

than 10% shall pass a No. 50 sieve.

4. Lime shall be mason's hydrated lime.

Under the heading, Mortar, the specifications read:

1. Mortar for all work shall consist of Portland cement, hydrated lime and sand, in the proportions of one (1) part of cement, one part of lime, and six (6) parts of sand.

In application, the joints of the facade were repointed so that the new joints are recessed 1/8 inch (1/3 cm). The bricks were cleaned of all excess mortar and the entire structure was sandblasted. However, on the exterior side walls, particularly the south one, and some interior walls, the mortar was not applied carefully. Many of the joints are flush and the mortar spills over onto the bricks (Figure 33).

Observations:

The mortar applied by Cavaglieri is darker than the existing and the joints are nearly twice the size of the original. In the new mortar, vertical hairline cracks are evident, particularly near boundaries between the old and new mortar. Although they appear to be dead cracks at the time of inspecton, they do suggest uneven horizontal movement between the old and new mortar. Some of the cracks are parallel which indicate vibration, probably caused by the subways rumbling below the building.

The Dairy, Central Park, New York

Historical Background:

The Dairy is situated amongst gentle rolling hills in the lower portion of Central Park in New York City (Figure 34). Like the Belvedere, another case study, its existence grew out of the 1857 Greensward Plan proposed by Frederick Law Olmsted (1822 - 1903) and was designed by Calvert Vaux in 1867. Considered to be the focal point of the lower Park, the Dairy was an accessory building to the 'Children's Department,' an area composed of playground, carousel, cottage and cow sheds. The function of the Dairy was refreshment and equipment center where city children could get fresh milk and rent play equipment. The granite structure served as the necessary kitchen and storage room with the attached loggia acting as an open shelter for tables and chairs.

The Dairy remained popular as long as Central Park did, but at the turn of the century the building became less frequented. By the 1950s the loggia and its spire had been demolished, and subsequent internal changes permitted the building to be used as an equipment storehouse for Park employees. In 1973 Joseph and Adrienne Bresnan developed a master plan for Central Park's rehabilitation. Restoration of the Dairy began in 1979 when private funds allowed the interior to be reconstructed. Unlike other structures in the park, the original designs for the Dairy have not survived. Restoration work and the reconstruction of the loggia are based on examination of old photos and analysis of surviving architectural remnants.

This project was also to be funded within the city's budget, but the 1975 crisis delayed it. Refinancing by fiscal foundations, banks, and other corporations allowed work to begin in 1979 at a cost of over $300,000. The Dairy now serves as a public hall for concerts, lectures, exhibitions, and park information.

Building Construction:

The Dairy's construction began in September of 1869. Vaux incorporated the building into its environment by constructing it in granite similar to that found in the park, and by placing the solid base

Figure 34: The Dairy

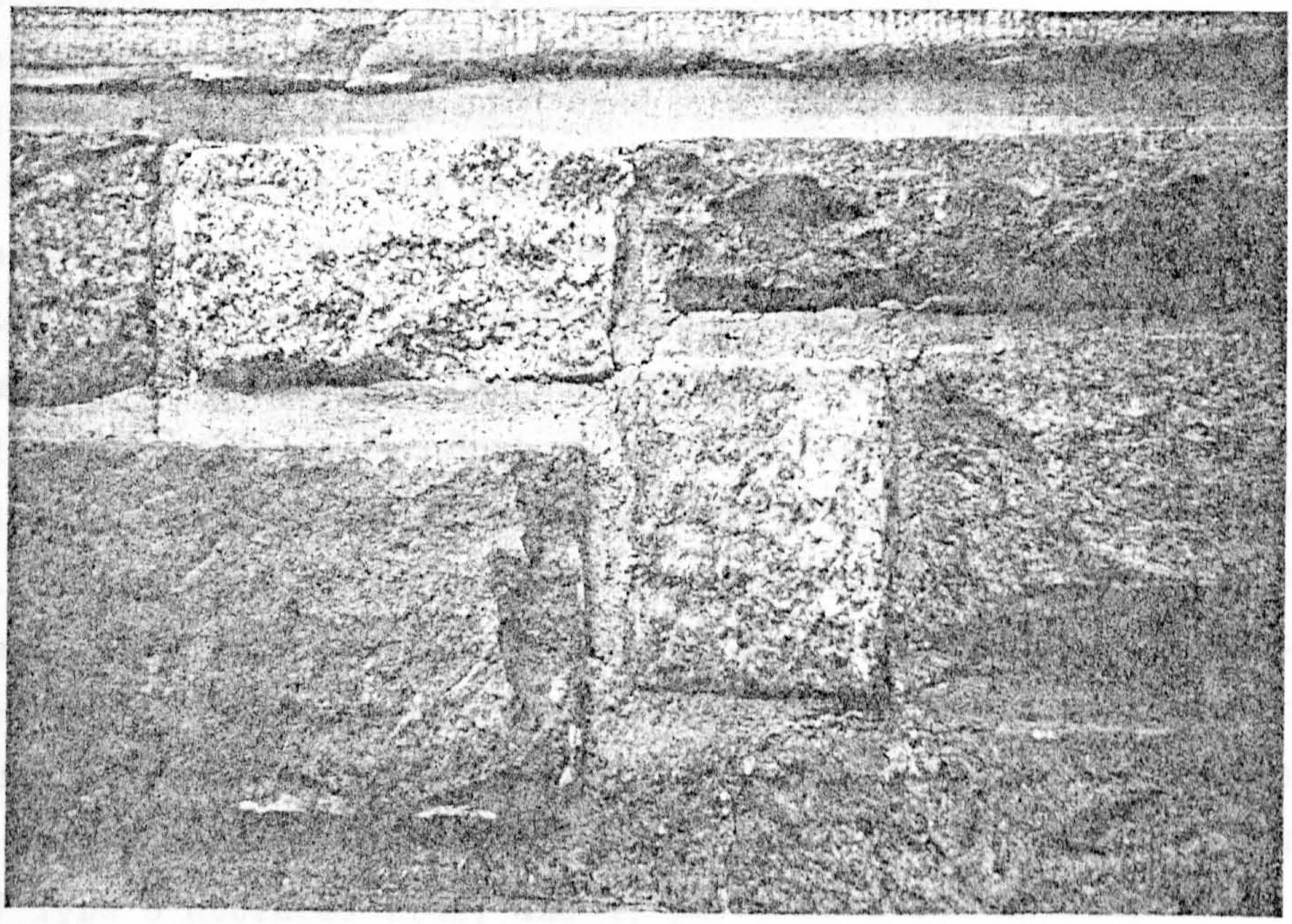


Figure 35

into a granite hill. Sandstone was used for the surrounds of all openings. The open loggia abutting the structure was placed to the south to obtain the maximum of warm, southern exposure. The back of the Dairy opened onto the 65th Street transverse road to allow deliveries to be made easily.

Designed in the Victorian Gothic style with allusions to other styles, the Dairy borrowed its window design from a country church, its roofline and hand railing from a mountain chalet, and its gambrel ceilings from a rural barn. The total sum amounted to $50,000. The open loggia was constructed on a granite base and assembled with the minimum of nails, in erector-set fashion, then finished with paint in a variety of colors.

Repairs:

When the use of the Dairy declined, the city decided to use the structure for equipment storeage. By the 1950s the deteriorated state of the wooden loggia and spire required their removal. In preparation for its new use, the eaves were stripped and a mezzanine floor was inserted in the main hall. Furthermore, the slate roof was replaced with shingles. Some respect for its former glory was retained when a small cupola with a cow-shaped weathervane was placed on the roof. The Dairy remained in this state until the restoration of the park began in the 1970s.

On the exterior, the granite needed repointing, and two of the stone arches and their windows needed replacing. The retaining wall for the loggia also needed reconstructing. The specification for the mortar showed the same care for the masonry units as the original specifications did. Ben Bryton, construction supervisor, said that originally the lime was obtained directly from limestone 'cooked' on the site. The stones were ground and placed in a kettle warmed by hot stones. They were continually heated for days until the limestone had burned to a useable lime. The Portland cement was a weak product typical of cement around the 1870s. In the 1979 restoration Bryton used ASTM Type N mortar: 1 part of C-150 Type I Portland cement, 1 part of C-207 Type S hydrated lime, and 4½ parts of E-144 masonry sand. The joints were repointed so that the new joints are recessed ¼ inch (2/3 cm).

The interior restoration proved to be more extensive than the exterior. The removal of the 1950s mezzanine floor revealed an original ceiling above. However, the old plaster and lath on this and the walls were in such a decayed state that they were removed and replaced with drywall attached to new metal studs. The addition of this wall treatment created a reveal of 1¼ inches (3-1/8 cm) near the two small circular windows at either end of the great hall. New windows were inserted, made of Lexan plastic.

With the completion of the loggia, which was given a base coat of fireproof epoxy paint per New York Building Regulations, the Dairy returned to its former condition. Completed in 1981 the Dairy nows serves the public in a variety of ways.

Observations:

Extreme care was taken in the restoration of the Dairy. Many of the techniques used in its construction were reemployed in its restoration. New stones were fashioned by hand; the loggia was joined using mortice and tenon joints. The mortar for the stonework was similar to the original, yet it conformed to ASTM standards. Granite may be one of the strongest masonry units available, but Bryton felt that a cushion of plasticity must exist for those units.

The job was completed in 1981 and a site inspection after 1½ years showed that the methods and materials used were appropriate (Figure 35). No deterioration of the masonry is visible.

Ticknor-Campbell House, Ann Arbor, Michigan

Historical Background:

The Ticknor-Campbell House (also known as the Cobblestone Farm house) is one example of an unusual building style involving a large quantity of mortar used in a decorative manner (Figure 36). Erected in 1844 for Dr. Benajah Ticknor by Stephen Mills, a mason trained in New York, this building depicts the Federal style and has cobblestones laid in herringbone rows as its sole building material.

The property, consisting of a tiny frame house and 183 acres, was purchased from farmer Charles Maynard in 1835 for Dr. Ticknor by his brother, Heman. Dr. Ticknor, then a U.S. Naval Surgeon travelling at sea, desired land in Michigan as an investment and for a retirement home. In the interim, the tiny house was occupied by Heman, his wife, and their seven children.

Benajah and his wife, Gessie, briefly visited Ann Arbor in 1840. The sight of nine people in so small a house no doubt prompted Benajah to erect the five bay, two storey cobblestone house for the two families. Construction began in 1844 and was completed within the year. In 1845 a kitchen, pantry, milkhouse, hired men's dormitory, toilets, and woodshed were added to the old frame structure, and the whole attached to the cobblestone building on its north or back wall.

From 1844 until his death in 1858, with the exception of several naval assignments, Benajah resided in the house. In 1860 Gessie Ticknor sold the farm to Horace Booth who eventually passed it on to his son. Nelson Booth bought additional acreage, built barns for thoroughbred race horses, installed a fountain in the front yard, and added a three-bay Italianate front porch.

In 1881 the farm was sold to William Campbell, a Scottish immigrant and merchant in nearby Ypsilanti, who proceeded to raise pure-bred cattle. Eventually the estate passed to his son, Clair, and his grandchildren, William, George, and Mary. For the 91 years the Cobblestone Farm remained in the Campbell family the stone house remained essentially intact.

After World War II extensive acreage was sold for housing

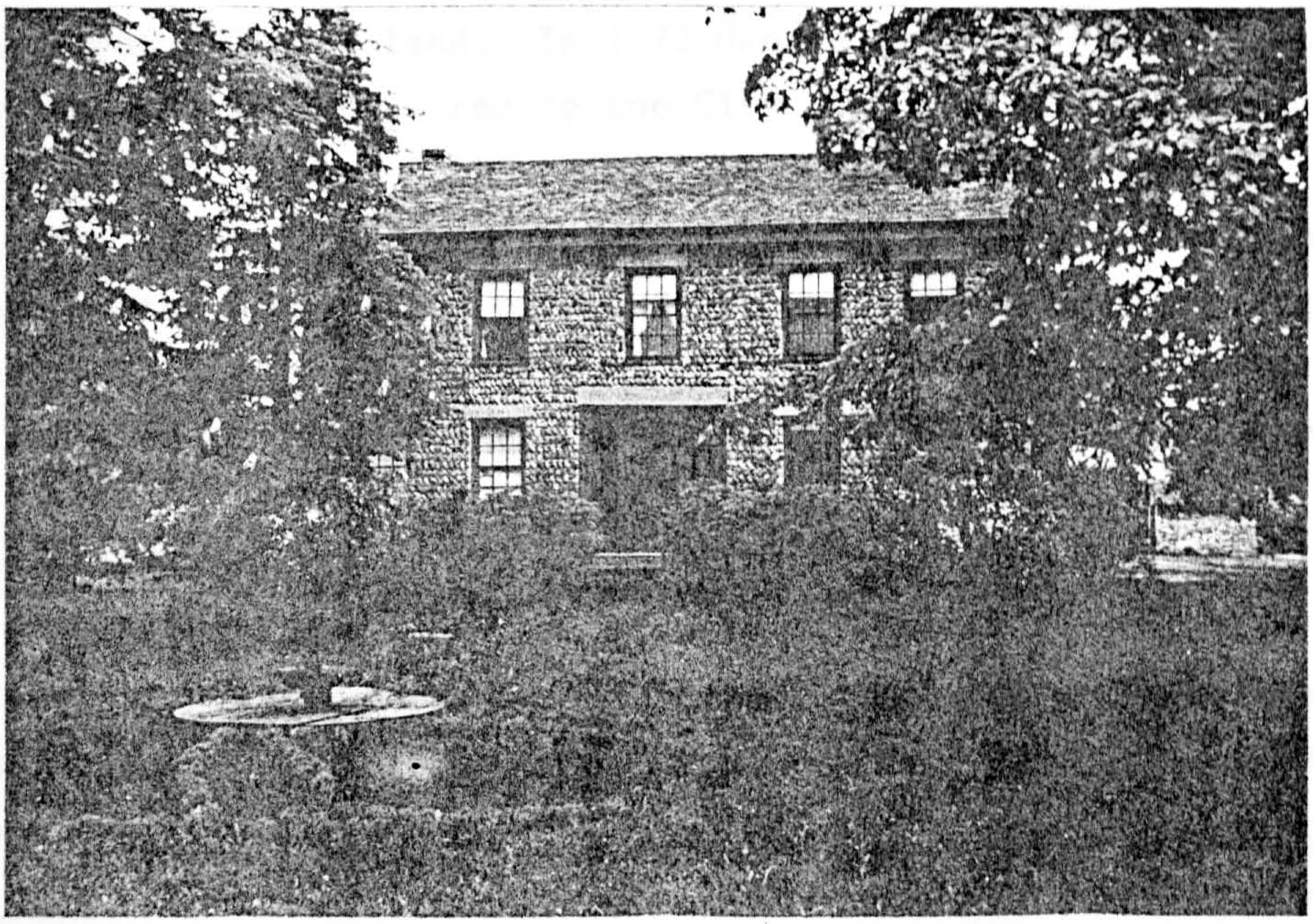


Figure 36: Ticknor-Campbell House

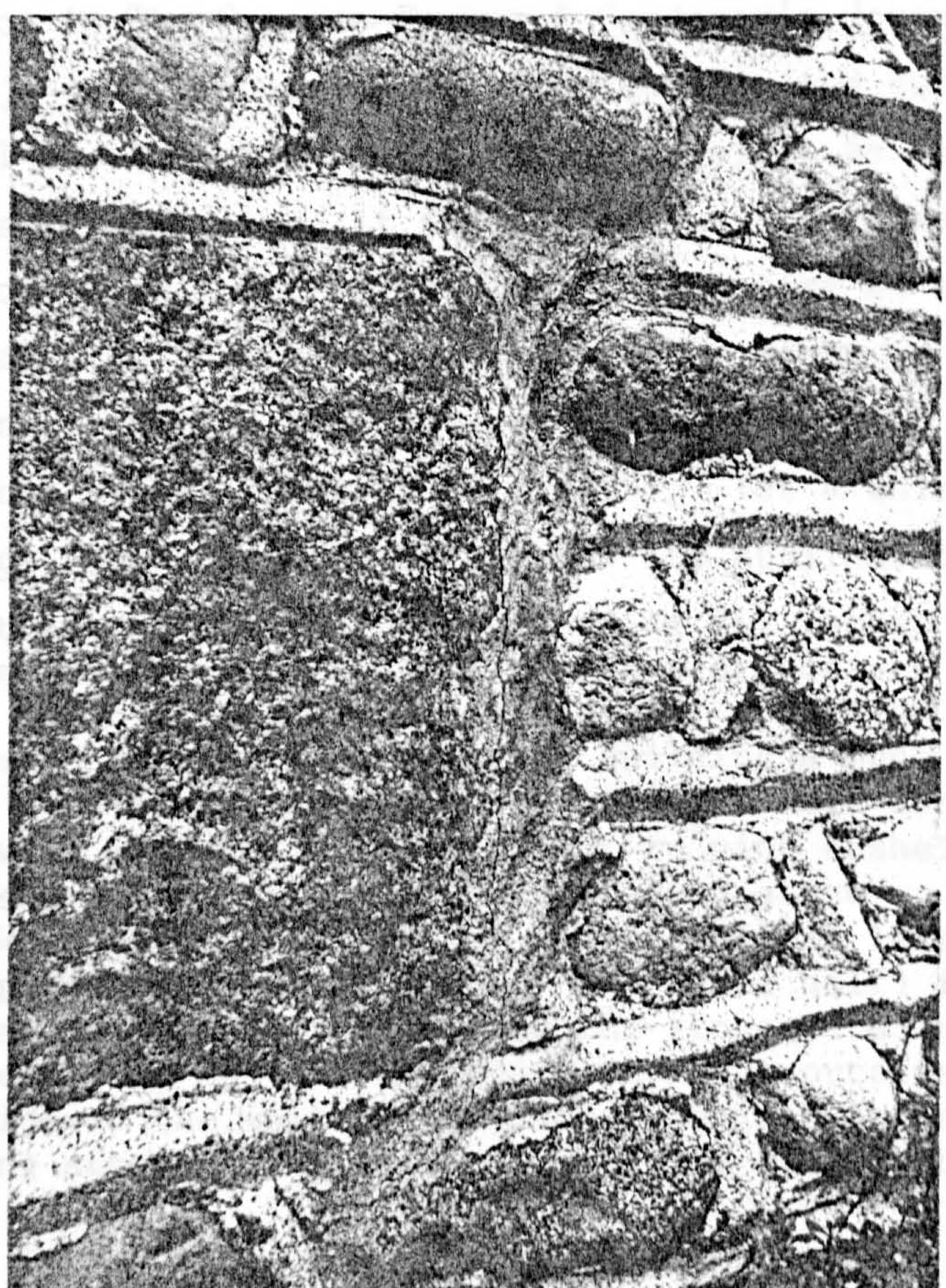


Figure 37

development and park land. In 1972 George and Mary Campbell sold the house and the last 4½ acres to the City of Ann Arbor to complete Buhr Park. Since 1974 the Cobblestone Farm Association, a group of volunteer citizens, has provided research and planning assistance, and has raised money for the restoration of the house and grounds as a working farm museum. The house is listed on the National Register of Historic Places and has been recorded for the Historic American Buildings Survey.

Building Construction:

Periodicals and treatises existed in the early nineteenth century, particularly in New York, to aid anyone interested in cobblestone construction. The Cultivator, a rural New York journal, and Edward Shaw's Operatie Masonry: Or, a Theoretical and Practical Treatise of Building (1832) were two examples. The topics discussed were mainly the size of the cobblestone and the mortar proportions. Authors agreed that the quality of sand with the lime was essential as the strength of the building depended on the 'goodness' of the mortar.

One mason in The Genesee Farmer & Gardener's Journal, a New York county journal, recommended: "The coarser and purer the sand, the stronger will be the cement and firmer the wall. As for the proper quantity of sand with lime, it depends on the coarseness and the purity. The proportion which I generally use, is from five to eight bushels of sand to one of lime in the stone."[19] Another mason in The Cultivator wrote: "Take the coarsest of sand...I used the common stone lime, one bushel to seven of sand."[20] Yet a third, also in The Cultivator, describes the mortar and its application:

> Cobblestones of any size not exceeding six inches in diameter may be used, but for the regular coarses on the outside those of two inches in diameter should be preferred. Small stones give the building a much neater aspect. Two inch stones are very neat, though three inch stones will answer...Mortar...eight to nine bushels of clean, sharp sand to one bushel of fresh stone lime...When the foundation, or cellar wall is levelled and prepared, a layer of two (or two and a half) inches of mortar is spread over it, and the stones are laid down into the mortar in two rows which mark the outside and the inside of the wall leaving about an inch between each adjoining stone in the same row. If the wall is to be

> grouted (mortar, sufficiently fluid, poured between the stones filling the interstices) the two rows are formed into ridges by filling the vacancies between the stones with mortar, and the space between these ridges (about a foot in width) is filled with such stones as are not wanted for the regular coarses. The grout is then applied. If the wall is not to be grounted however, the mortar should be carefully pressed around each stone, making the wall solid without flaw or interstice. When one coarse is levelled, begin another.[21]

Cobblestone masons heeded this advise, but also used their knowledge and experience to vary the proportions needed for a durable mortar. On the whole, 1:7 - 9 lime:sand was used.

As Stephen Mills was a New-York-trained mason, it is not surprising that the Cobblestone Farm house bears considerable likeness in construction techniques to those found in New York state. Mills used a lime mortar whose original constituents were burnt limestone from a nearby lime pit and local coarse sand.[22] Although the mortar has not been analyzed, it is believed to be a 1:7 - 9 lime:sand due to the building's close connection to similar structures in New York.

Similar to the description given by the third mason in The Cultivator, Mills encased small, fist-like stones of roughly a 2 - 3 inch (5 - 7½ cm) diameter into a herringbone mortar bed with a one-inch surround. The mortar was pressed around each stone to form a tight, clean bond. Mills also employed another common technique: small stones were used on the front and side elevations while the back wall consists of larger, more angular stones. The house was completed with such precision and skill that few repairs have been necessary over the 139 years (1844 - 1983) of its life.

Repairs:

Based on surviving records and visual examinations, the cobblestone portion of the Ticknor-Campbell House has been repaired a known total of three times: pre-1972, 1973, and 1979.

Pre-1972: Stonework on the front of the house near the southeast corner was repaired by George Campbell, the last owner of the house. He used a formula of 3 parts of sharp sand to 1 part of commercial mortar mix. The sand came from a gravel pit behind the house and the mortar mix was a premixed formula of 1:1 Portland cement:lime.

1973: Cracks on the east end of the stone house were repaired by the City of Ann Arbor in 1973 before the Cobblestone Farm Association started restoration. Ordinary ready-mix mortar was used and no attempt was made to match the original mortar.

1979: The stonework above the back door to the stone portion of the house (on the east side of the wooden ell) was repaired in 1979. The stone mason, Roy Gerow, used 3 parts of mason's sand to 1 part of commercial mortar mix. The stone mason cannot identify the type of mortar mix used. The bag was left from a previous repair of the adjacent brick supports of the cellar door. It was probably a readily available commercial mortar mix of lime and cement.

Between 1974 and 1980, all of the chimneys were repointed and two were completely rebuilt--the chimney on the wooden kitchen ell and the southwest front chimney on the stone portion of the house. Old bricks were employed, but modern mortar of the kind used by present-day brick masons was used.[23]

Observations:

Although color-matching in all three repair cases was not achieved and the skill in which the mortar was applied has not been the best, all but the 1973 repair appear weather-tight and in good condition.

The pre-1972 repair by George Campbell shows his attempt to recreate the original mortar and its herringbone pattern. Despite the use of similar local sand, the color was not the same, nor did it age to match. The herringbone design is duplicated, with extreme difficulty, only in a few areas.

The 1973 repair has begun to crack vertically once more and the patch has never matched the existing in color (Figure 37). When the Cobblestone Farm Association undertook the restoration in 1974, they attempted to avoid large areas of repointing with gray Portland cement to prevent the 1973 repair problems from reoccurring. No attempt was made to duplicate or match the ingredients and design of the original mortar as the C.F.A. felt it was a lost art.

The Chapel of the Good Shepherd, Roosevelt Island, New York

Historical Background:

The Chapel of the Good Shepherd is situated on Roosevelt Island in the East River of New York City (Figure 38). Originally called Blackwell's Island after the farming family residing there, the island was named Welfare Island in the 1830s when it served as grounds for housing the City's poor and sick. Hospitals, jails, and houses were constructed and later, in 1889, the chapel was erected for use of the almshouse's inmates.

In 1935 the prisons were torn down and the occupants transferred to the new Riker's Island penitentiary. The use of this island declined, but the stigma associated with the poor and sick continued. In the 1970s Welfare Island was renamed yet again: Roosevelt Island after Franklin Delano Roosevelt. The New York State Urban Development Corporation proposed a total revitalization, creating a 'new-town-in-town.' Their attempt to attract the higher-income citizens was unsuccessful; they did, however, build a good quality housing project for low-income families.

Today, the majority of the island's occupants are lower-income families. The Chapel of the Good Shepherd has been turned into a community center, and the immediate surroundings into an urban plaza. The island is pedestrianized due to its small size. As such, riverfront walks, landscaping, and plazas abound. An aerial tramway provides a much-used link to Manhattan.

Building Construction and Repairs:

The Chapel was erected by George Bliss, Esq., a New York banker, in 1889 for $75,000. Bliss employed Frederick Clarke Withers as architect, and Philip Herrman's Sons as contractors. The design was in the Gothic Revival style, typical of other, earlier structures on the island. The building was constructed of native, rock-faced granite as high as the water table; the walls above consisted of Croton front brick with sandstone trimmings of Belleville stone.[24] Red mortar was used to

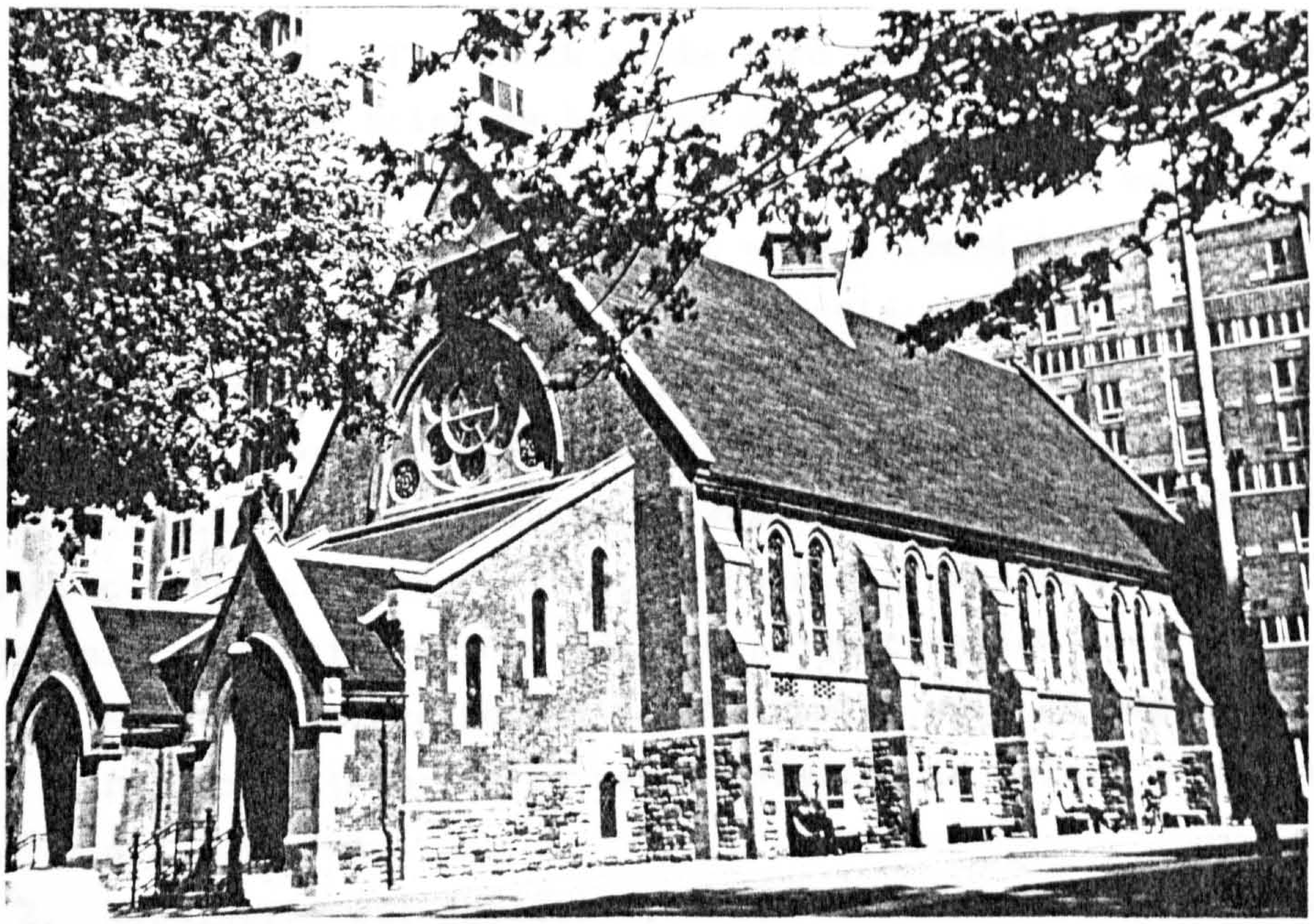


Figure 38: The Chapel of the Good Shepherd

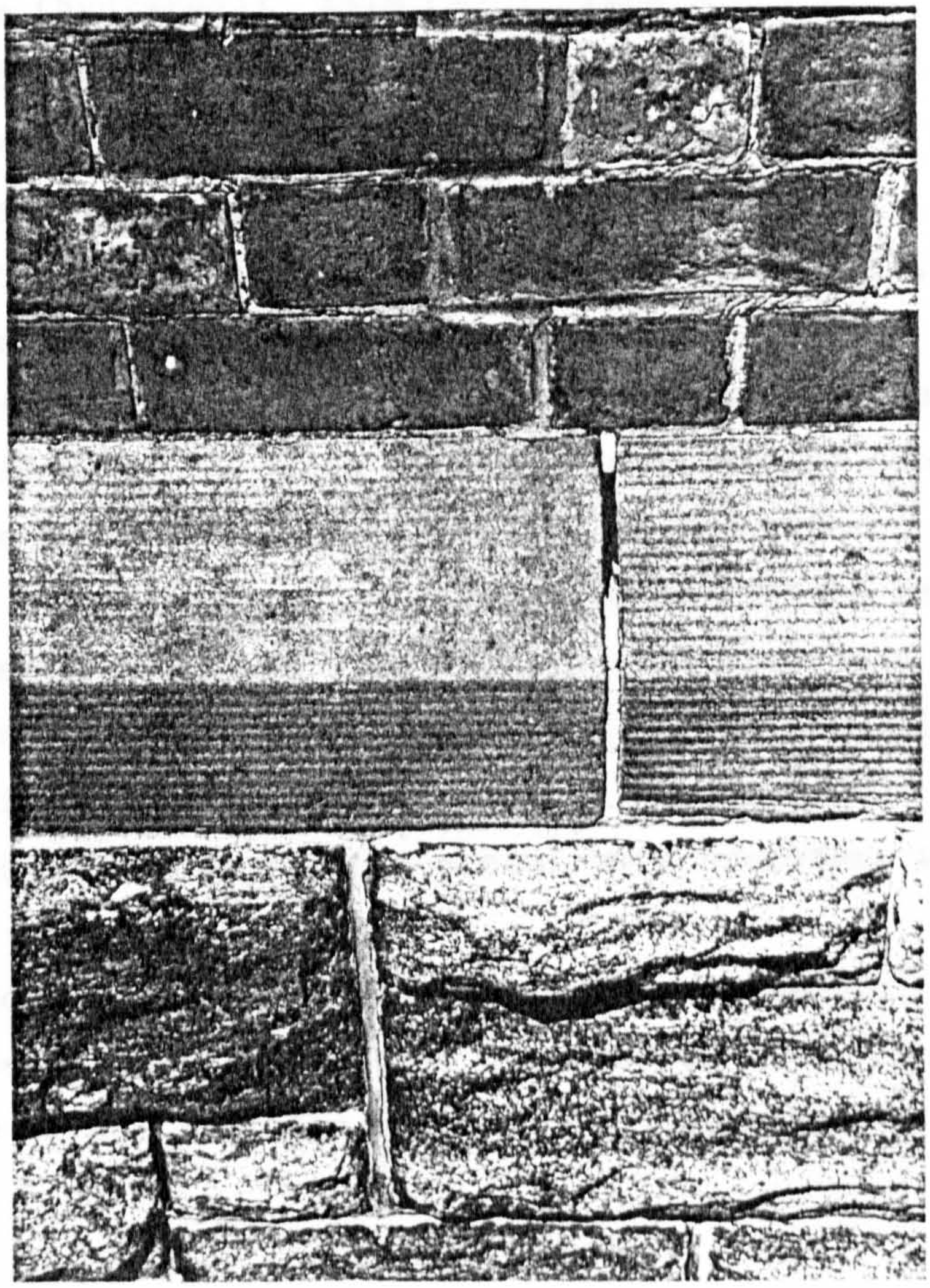


Figure 39

point all brickwork. The brick walls were cavity walls faced inside with brown enamelled brick as high as the stone string course under the windows. Above the course, buff-colored pressed brick was laid in red mortar. All doorways and the chancel were trimmed in limestone. The interior roof was open-timbered using Georgia pine.

In 1965 the City of New York performed some repair work on the chapel using a pure cement mortar in repointing the required areas. In 1973 Giorgio Cavaglieri, Architect, was hired by the Urban Development Corp. to convert the chapel into the community center. The mortar-related specifications for the project called for:

1. Remove existing poorly patched brick work on exterior walls and replace with brick to match existing in color, size, texture and jointing.
2. Repointing all defective, loose and missing mortar joints in all exterior exposed masonry walls.

The materials employed were to be as follows:

a. Portland cement: ASTM C-150, Type 1
b. Lime (hydrated): ASTM C-207, Type S
c. Sand: ASTM C-144
d. Common brick: ASTM C-62, Grade SW
e. Face brick: match existing
f. Mortar: ASTM C-270, Type S for exterior work, Type N for interior work.[25]

Type N mortar in ASTM C-270 is defined as: a) 1 part Portland cement; b) 1/2 to 1-1/4 parts hydrated lime; and c) sand, not less than 2-1/4 and not more than 3 times the sum of the volumes of the cement and lime used.[26] Type S mortar in ASTM C-270 is defined as: a) 1 part Portland cement; b) 1/4 to 1/2 part hydrated lime; and c) sand, not less than 2-1/4 and not more than 3 times the sum of the volumes of the cement and lime used.

The specifications for the actual work procedure were given as follows:

1. Before new work is started, remove loose mortar and wet the exposed joint thoroughly not less than two hours before laying new work. Existing masonry shall be properly prepared and

cleaned to allow for new masonry and proper bonding.

2. All defective, missing and loose mortar joints in exterior exposed brick work shall be cut back at least one inch deep, all loose particles removed, joints thoroughly cleaned out and wetted and solidly filled with pointing mortar, tooled to match existing jointing. Mortar shall be pigmented, if required, to match color of existing mortar joints.
3. New brick work shall be laid up in bond, jointing and pattern to match existing and in a manner to uniformly blend in. Walls and filled-in areas and stone backing shall consist of brick and/or block as required and shall be solidly built-up with full mortar joints.
4. Use all reasonable means to keep the exposed masonry work clean while being laid, and particularly to keep it free from mortar on exposed surfaces. Mortar drippings shall be immediately removed.
5. All exterior exposed masonry walls shall be cleaned down and properly prepared ready for steam cleaning.

The Cavaglieri repair caused all neat cement mortar from the 1965 repair to be raked out to a depth of 1 inch (2½ cm). Today the masonry walls consist either of the original red mortar or the red mortar inserted in 1973-4.

Observations:

Initially no damage was apparent from the 1965 repair work, but in 1973 when the Urban Development Corp. began construction of the apartment houses, their dynamiting caused settlement cracks. The cracks appeared in the brick, not in the surrounding cement mortar, suggesting that dense mortar forced the brick to absorb movement.

The Cavaglieri repair was 8 years old when it was examined in the Spring of 1981 (Figure 39). The masonry appears exactly as the specifications required with no visible crazing or cracks.

The Belvedere, Central Park, New York

Historical Background:

The Belvedere is situated atop a rock-faced schist called Vista Rock in Central Park, New York City (Figure 40). Its existence grew out of the 1857 Greensward Plan for the park which proposed a towerlike structure to be situated on the vantage point of the rock outcrop. The Croton Reservoir Board, owner of the property and the adjoining lake, ceded the summit to the City of New York in 1867, and the foundations for the Belvedere commenced.

Calvert Vaux (1824 - 1895), the architect for several buildings in the park, completed the plans for the Belvedere in 1867--a structure that would be the park's most extravagant and costly yet. His original designs, however, were never carried out. After consulting with Jacob Wrey Mould, architect-in-chief, it was decided to eliminate all embellishment and omit one of the castle-like towers. Construction then went ahead.

For years the Belvedere served only as a haven, lookout, or as the "object of a typical stroll." In 1919 a meteorological and astronomical observatory was set up in the structure, one of several established in Central Park under 1869 legislation. As a result, visitors came less frequently, vandals more often, and the Belvedere began to deteriorate. Two pavilions were removed prior to 1930 and by 1960, when the installation of automatic weather equipment eliminated the need for men on the site, the building was in desperate need of attention.

In 1973 Joseph Bresnan, Director of Historic Parks, and Adrienne Bresnan, Assistant Director of Capital Projects, prepared a preliminary master plan for the restoration of Central Park. The Belvedere was identified as a critical area. The project was delayed by the City's 1975 fiscal crisis. Refinancing of the City's budget in the late 1970s finally allowed the project to begin.

Restoration of the Belvedere was completed in 1982. An exhibit will shortly be opened within it on its history and geology, and visitors will once again be able to climb the tower to observe weather equipment in use and to enjoy the 'belle vedere' or 'beautiful view.'

Figure 40: The Belvedere

Building Construction:

Erected in granite on rock-faced schist, the Belvedere was designed using a maximum of Victorian eclectic design motifs as Vaux planned for it to be the focal point of the entire park. Originally he conceived a structure of Gothic inspiration, but Norman in allusion. The main building would have two cylindrical towers with conical roofs of polychromed slates and, along with the pavilions, would have Moorish-influenced bartizans or overlooks, and one or more arcaded loggia balconies and terrace. Reached by walking through the Ramble, a contrived wild and virgin territory, the Belvedere would strike the stroller as a protective, yet welcome, haven. Visitors would climb to the bartizans and towers, and get spectatular views of Fifth Avenue and other profiles of the city.

Vaux's blueprints were heavily altered when the large financial sums budgeted for the project appeared to be inadequate for the completion of the terrace. Vaux and Mould agreed to eliminate all extravagant detailing and omit one of two towers on the main structure. This latter removal alone saved $50,000.

Repairs:

The Belvedere served the public until 1919 when the United States Weather Bureau took over the building. In order to maintain offices here, the Bureau winterized the structure and altered the conical tower to create a weather station. All the arched masonry openings were fitted with doors and windows, and a boiler and toilets were installed in the basement. Rooms were created within the open spaces of the structure's interior.

The most dramatic alteration at this time was to the conical tower. The slate roof and parapet were removed and replaced with a crenellated cut-stone parapet and flat roof for the weather monitoring equipment.

No repairs were carried out after the 1919 renovations and the Belvedere fell into a state of disrepair. By 1970 only the main structure for the Weather Bureau remained. The pavilions were gone and the terrace walls had collapsed, encouraged no doubt by vandals, into Belvedere Lake below.

The 1980 restoration itself involved returning the Belvedere to its original state and yet maintain the winterized standards completed in 1919 to enable the structure to be used year-round. In the main structure, the granite stones were repaired or replaced as necessary, and a mortar similar to the original was chosen. Portland cement pointing haphazardly applied around the stonework in 1919 was raked out and replaced with a mix of 1 part of Portland cement, 1/8 part of lime, and 2½ parts of sand. Ben Bryton, construction supervisor, said the mix was ASTM Type S mortar with 50% less lime, as this more closely matched the original and the granite could withstand a stiffer mix.

Parapets were rebuilt with new stones and those retrieved from Belvedere Lake. Corroded cast iron support beams for floors and ceilings were replaced with steel. Funding even allowed the two pavilions, removed prior to 1930, to be totally reconstructed. Details for the millwork, castings, and slates were taken from surviving documentation. The most visible alteration occurred in the single tower of the main structure. The restoration architects decided to return it to its original state, complete with conical, polychromed slate roof.

Observations:

The restoration of the 1980s was achieved with extensive care being taken to match the old stone, slate, and mortar. The architect specified a Type S mortar with only 1/8 part of lime in the belief that it was similar to the cement mortar used in 1870.

The completion of the restoration of the Belvedere was over one year old when a visit was made in December 1982. There were no visible signs of cracking or crazing to indicate that the chosen specification was incorrect.

Faneuil Hall and Quincy Market, Boston, Massachusetts

Historical Background:

Market development on the Boston, Massachusetts waterfront began in 1742 when Faneuil Hall market was built (Figure 41). The structure got its name from Peter Faneuil, who gave it to the city. The 100 x 40 foot (30 x 12 m) market burned in 1805, but was rebuilt twice that size by Charles Bulfinch shortly afterward. Bulfinch designed the structure in the "colonial" style, or more formally, in the English Baroque style, being influenced by Christopher Wren.

Business proliferated and, in 1822 on a nearby site, Josiah Quincy began the first public development project in the United States: an enormous new market, 535 x 50 feet (160½ x 15 m), flanked by similar-sized warehouses (Figure 42). The total cost was $1.1 million. Alexander Paris designed the buildings in the Greek-revival style and planned for a granite facade over a brick and iron framing system. In 1825 the cornerstone was laid.

The market was completed in 16 months. Market activities continued until World War II, but over the years tenants made various alterations. Several storefronts and fenestration schemes were changed and additional storeys were constructed in some places, particularly in the north and south flanking buildings.

By the 1950s the market buildings were noticeably deteriorating. Mechanical systems failed as maintenance diminished. Most merchants moved out. The Boston Redevlopment Authority, known for its ruthless demolition projects, was to determine the fate of Quincy Market.

However, concerned citizens opposed demolition of the structures, and in 1966 and 1968 Frederick Stahl and two partners made feasibility studies to reuse the buildings. Stahl and Bennett, developers, received a two million dollar grant to start rehabilitation work. A major project for the firm of Benjamin Thompson, Architects, it fell through in 1972 for want of finances. The Rouse Company then entered with a new proposal, but it took them two years to convince Boston bankers that the financial arrangements would be successful.

The restoration work started in 1975 and was completed in 1978.

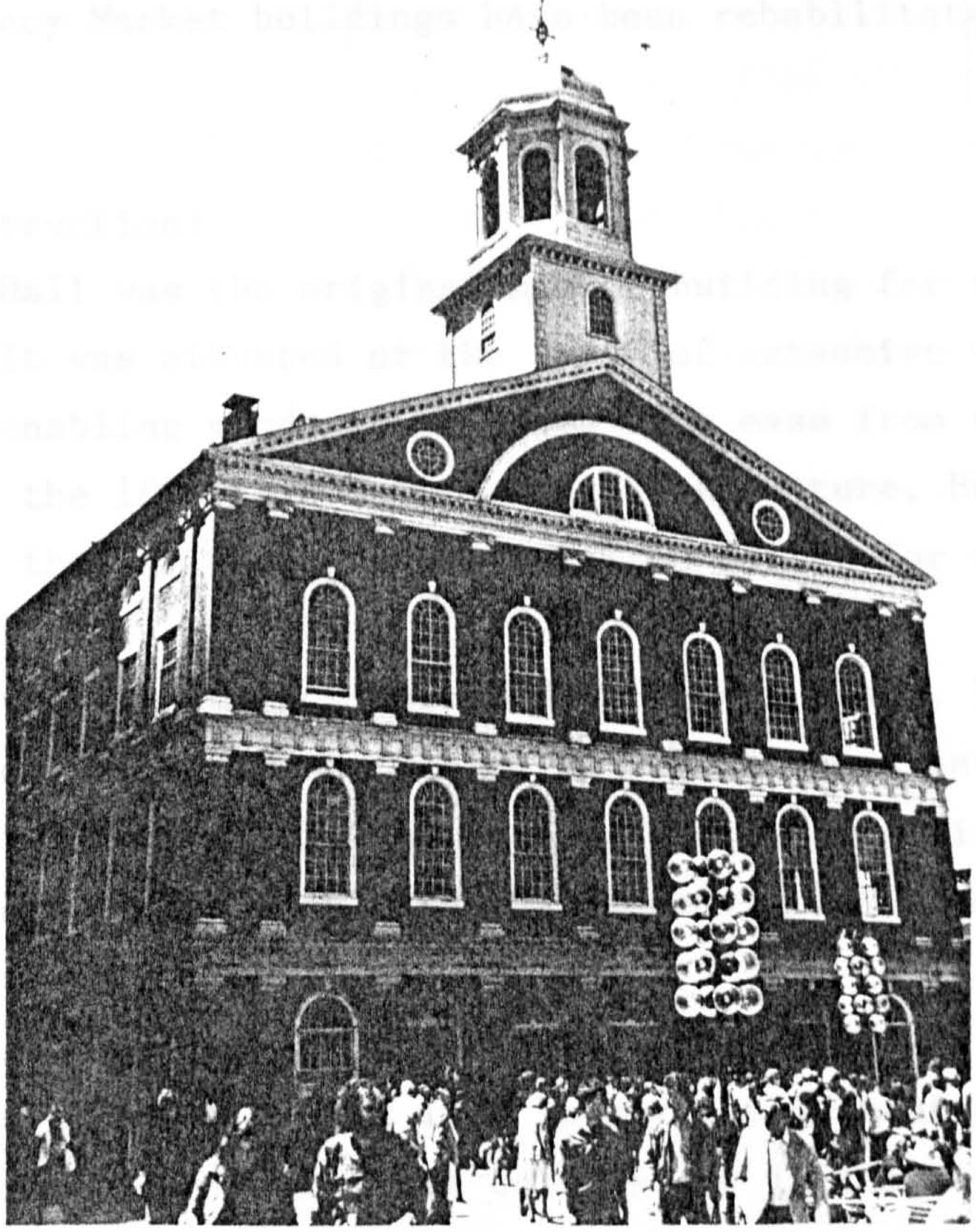


Figure 41: Faneuil Hall

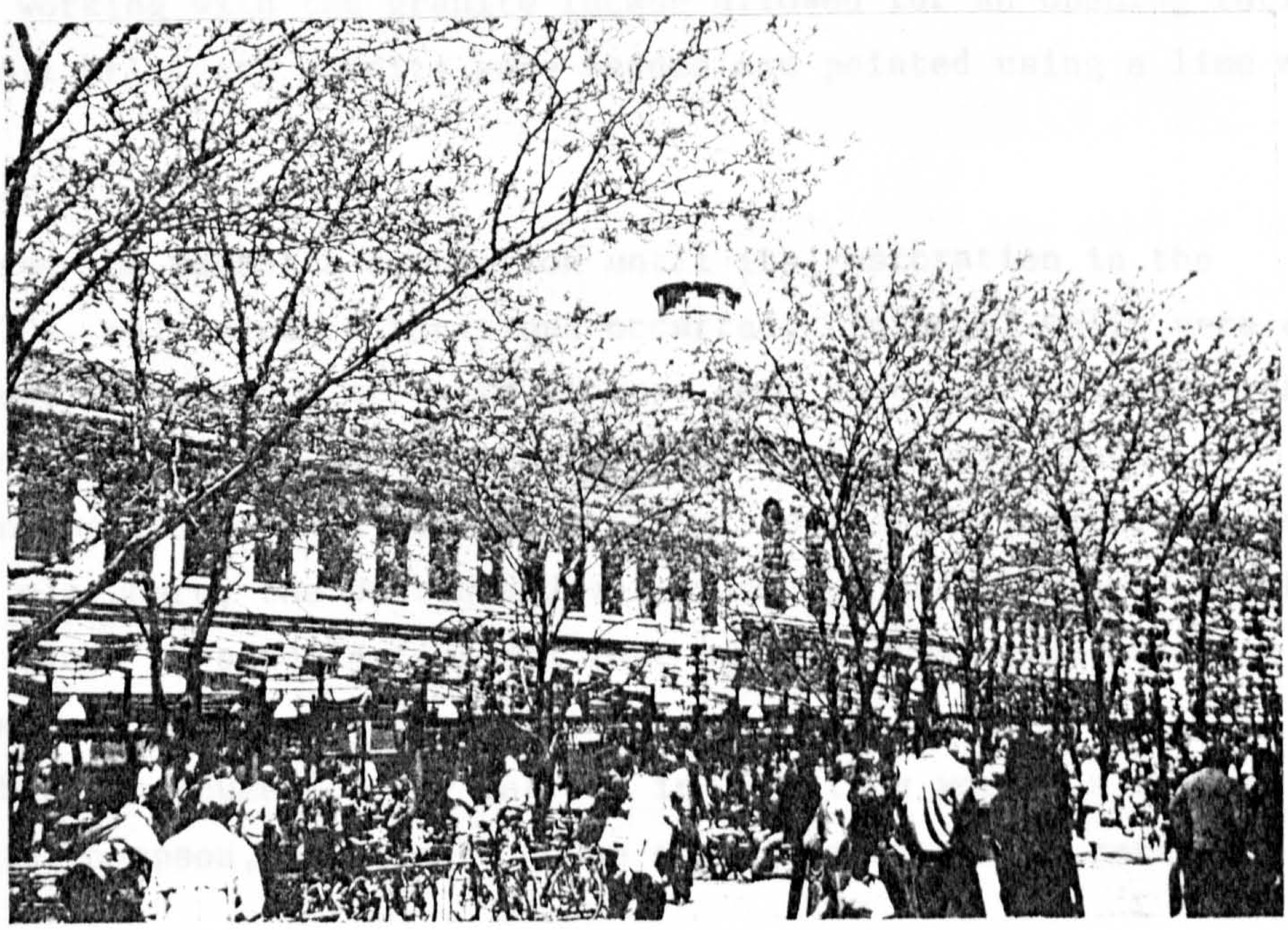


Figure 42: Quincy Market

All three Quincy Market buildings have been rehabilitated, one row at a time.

Building Construction:

Faneuil Hall was the original market building for the Boston waterfront. It was situated at the front of extensive wharves and ship berths, thus enabling goods to be taken with ease from ships to the market. When the 1805 fire demolished the structure, Bulfinch reconstructed the hall using brick and lime mortar for the load-bearing walls.

In 1822 when the Quincy Market development began, Faneuil Hall became the focal point in the design with warehouses and a larger market surrounding it. Many of the wharves and berths were filled in to provide the land needed, and thus the shoreline was advanced and straightened.

The designs produced by Paris were highly innovative and modern for the time. His creative use of iron is still illustrated in the first-floor framing system. Some columns are in compression, supporting the upper floor, and some are in tension, supporting the ground floor in part from above. Transport by canals allowed Paris to use enormous granite columns, some measuring 22 x 3 feet (6-2/3 m x 90 cm). This system working with the granite facade allowed for an opening ratio of 50%. All brick and granite were bedded and pointed using a lime mortar.

Repairs:

From the market's completion until its restoration in the mid-1970s, only minor alterations occurred. Internal walls were changed or moved, and dormers or extra storeys were added as various merchants altered their stores within the building to fit their needs.

In the 1950s and 1960s in an effort to prevent merchants from moving elsewhere, the Boston Redevelopment Authority "upgraded" the market place by sandblasting all four buildings and repointing as necessary using a cement mortar.

When the Rouse Company entered in 1975 they worked alongside Benjamin Thompson, Architects. One concern centered on returning the market to its original state. A fundamental question was whether to leave the altered roofline or to remove the added storeys, but eventually the old roofline was restored. Some controversies arose over the replacement of older sash windows with single panes, and the installation of new skylights that produced a strong visual effect at night, but these were minor issues. The main benefit was that the structures were to be saved and reused.

Repointing was done using a Portland cement and lime mortar. Thompson stated that the mortar for face brick and concrete block was to be made to the following specifications.

I. ASTM No. C-270 Type N Mortar

a) 1 part Portland cement: ASTM No. C-150, Type 1-R2
b) $\frac{1}{4}$ - $\frac{1}{2}$ part hydrated lime: ASTM No. C-207, Type S
c) sand, not less than $2\frac{1}{2}$ nor more than 3 times the sum of a) and b) combined by volume; ASTM No. C-144

II. No anti-freeze admixtures are to be added to I.

III. All materials are to be the same and used throughout the project.

These specifications further stressed that color and texture matching were to be carried out throughout the project.

Observations:

During the pre-Rouse repairs the cement mortar was applied in a haphazard fashion to the brickwork of Quincy market. The heavily pitted bricks were surrounded by a light gray cement. In many areas no effort was made to recess the joints or wipe off brick surfaces where it had slopped over. The cement mortar has not adhered to the old lime mortar, causing cracks and even loose mortar in many of the joints. The sandblasting has marred the brick considerably and, unfortunately, has caused the brick to deteriorate further over the years.

The repairs conducted in 1975-78 have, on the other hand, weathered and aged well (Figure 43). No cracks or crazing are visible in this new

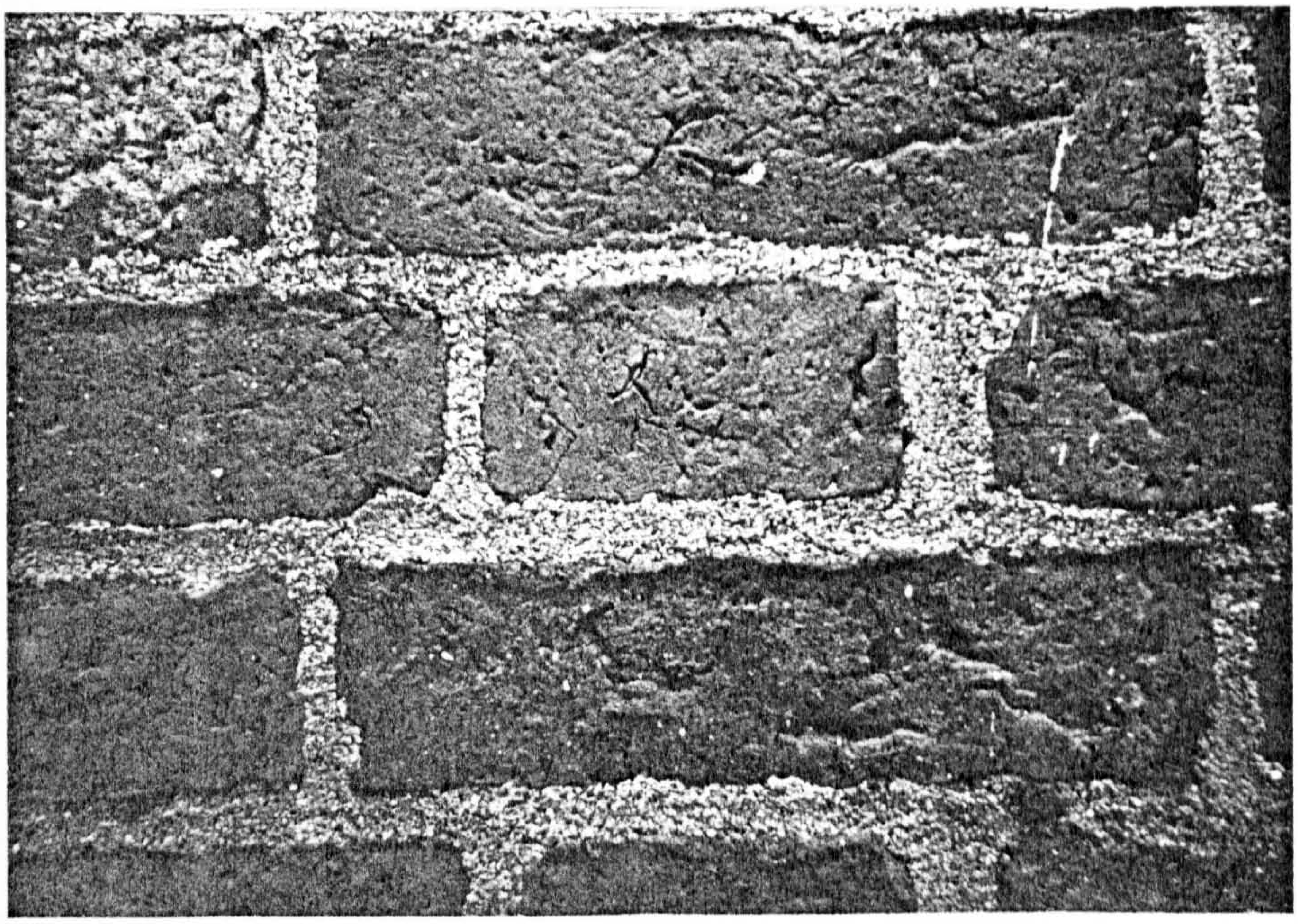


Figure 43

mortar; it is a noticeable improvement over that applied by the Boston Redevelopment Authority.

Chesterwood, Stockbridge, Massachusetts

Historical Background:

The land on which Chesterwood now stands was originally the Marshall Warner farm, located near Stockbridge, Massachusetts in the Berkshire Hills. Daniel Chester French (1850 - 1931), renowned for his sculptures including the seated Lincoln for the Lincoln Memorial in Washington, D.C., discovered the site in 1896. He and his wife were seeking a summer residence to retreat to from the opressive heat of New York City. French purchased the farm for its "beautiful and soul-satisfying" view of the Housatonic River and Monument Mountain, and employed his friend and architect, Henry Bacon (1866 - 1924), to design a studio and house. Construction of the studio began in 1898, followed by the two-storey, 17-room, Georgian Revival house in 1900-01.

Chesterwood was typical of summer residences at the turn of the century (Figure 44). The studio was the exception. Here French incorporated railroad tracks and 22-foot high double doors into his design to allow all his sculptures to be pushed on a flatcar outdoors for the artist to study in natural light.

Chesterwood was the summer residence of the Frenches until 1969. D.C. French died in 1931 and his wife in 1939, at which time the estate passed to their daughter, Margaret French Cresson. In 1969 she donated the property to the National Trust in memory of her father. Chesterwood is both a National and Massachusetts Historic Landmark.

Building Construction:

The studio and house were built using conventional building methods. Prior to construction, French made extensive specifications for Bacon to follow, incorporating materials from the old farm buildings slated for demolition. He also examined governmental reports and other documents on Portland cement to determine its suitability in mortars and exterior stuccos.

In 1898 work on the studio began. The Warner barn was moved to the back of the property and the new studio, built of wood and covered with

Figure 44: Chesterwood

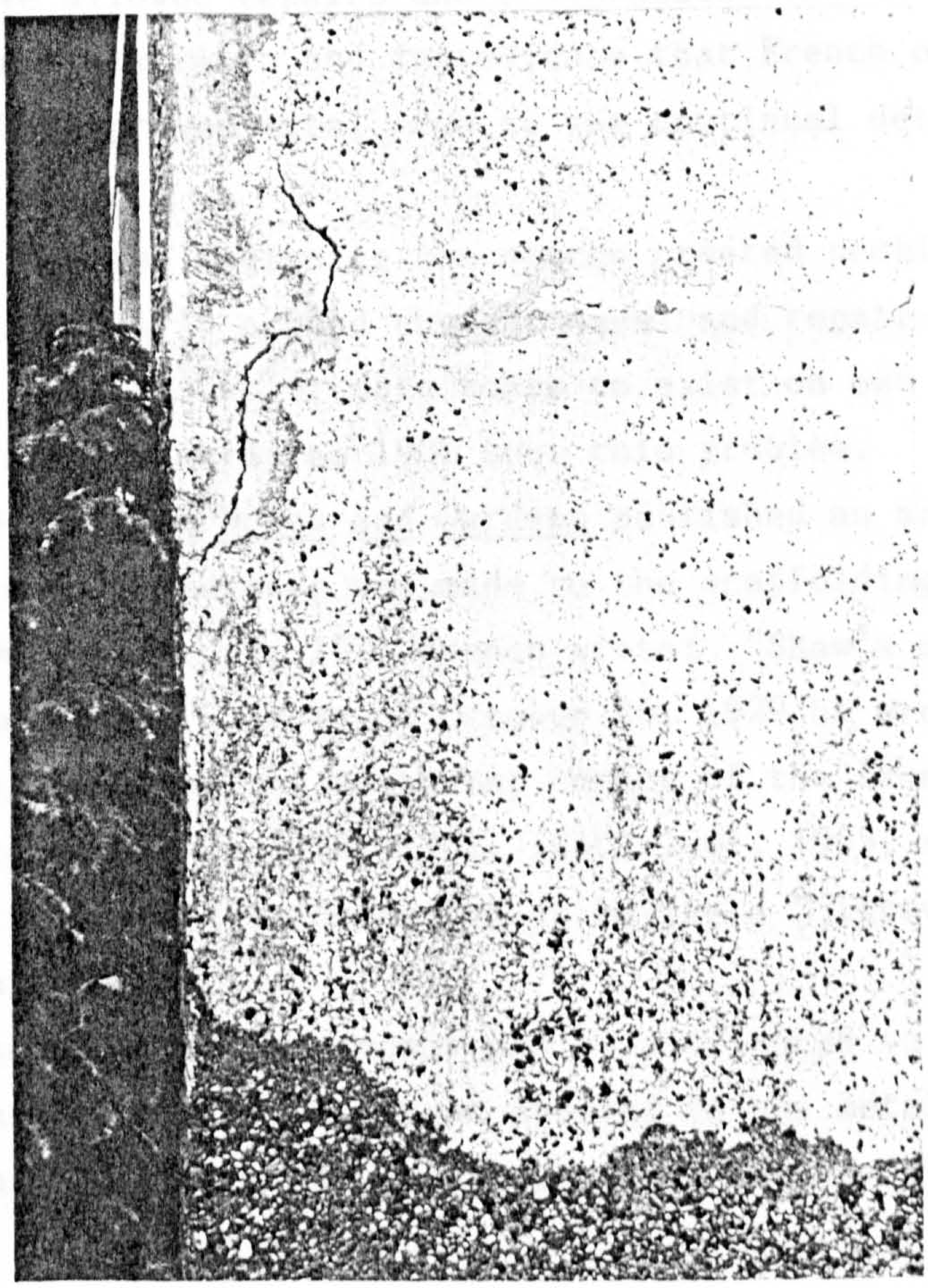


Figure 45

metal lath, was placed on the barn's foundations. The entire structure was then coated with a render created by French to produce "an excellent surface of char grey color." The plaster or stucco French decided upon was of "pure Portland cement mixed with sifted coal cinders and marble dust."[1] The only deviation from Portland cement occurred in the chimney, where French requested that it be "of good common brick laid in lime mortar" and covered with Portland cement.

Replacing the unsuitable farmhouse, the new house was constructed in 1900-01, with materials and procedures used previously in the studio. French's diary states that, once again, "Bacon put marble and coal chips into the stucco to give it its color and appearance," and that the application of the stucco was completed, except for the chimneys, by June 20, 1901.

Repairs:

The notes French, and later others in the family, maintained over the years have allowed repairs and restoration work to be undertaken, using the exact mix ratio and ingredients that French originally specified. This proved vital, due to the continual deterioration of the stucco.

Almost from the beginning the stucco created problems. Spalling occurred, particularly around the chimneys, and repairs were never the exact color, causing two or more tones to exist on one surface. Photographs from as early as 1902 show this problem.

In 1909 American Homes and Gardens published an article on the French estate and reference was made to the scaffolding around the chimneys. On October 31, 1921 French wrote: "Shaw's man is mending the stucco on the house." Again on October 26, 1929 he wrote: "Sermini is patching the stucco on the southwest corner of the front of the house." References continued in 1930, 1932, 1940, 1961, 1965, and 1977. At one point the stucco was even described as having a "jigsaw puzzle effect"(Figure 45).

The repeated need for repair can be attributed to three factors. French did not have a scratch coat applied to the metal lath before the two-coat finished stucco was applied. Also, the use of Portland cement may have proved detrimental as its hard and heavy qualities would not have had a firm backing to adhere to. Thirdly, the spalling might also be attributed to shrinkage of the Portland cement.

During the summer of 1982 the National Trust went to considerable expense to restucco the house. Coke was imported from Johnson City, Pennsylvania and a 10-ton crushing machine was hired to produce chips closely matching those French used. A scratch coat was employed this time and lime was added to the mix, both in the hope of making this repair a long-lasting one.

The specifications called for the scratch coat to be made of 3 parts of sand, 1 part of Type 2 gray Portland cement, and 1/2 part of hydrated lime. This was to be mixed until plastic and applied to galvanized, expanded metal lath, and then scarified. The finish coat consisted of 2 parts of Type 2 gray Portland cement, 1 part of hydrated lime, 3 parts of sand, 3/4 parts of marble chips, 1/2 part of "Dairy Clean" (another form of marble chips), and 2 parts of coal cinders and crushed coke. The coke was screened through 1/2" and 1/4" sieves and that retained on the 1/4" screen was used in the finish coat. Once the ingredients were mixed with water, the finish coat was applied immediately using wood floats. After 2-3 hours the entire surface was misted to expose the aggregate. To "age" the stucco to match the old it was recommended that it be wiped with muriatic acid of a ratio of 1 part of acid to 10 parts of water, but this was not done as it was thought that the stucco would age properly on its own.

Observations:

Chesterwood was constructed before American standards had been compiled on Portland cement. Cement was a product rapidly becoming popular in the building industry and French did build in a conventional manner. However, the repairs carried out by the National Trust indicate that the original mix of 2 parts of cement, 3 parts of sand, 1¼ parts of marble chips, and 2 parts of coal cinders was too rich in cement and that a scratch coat should have been used for such a rich mix.

The 1982 repairs were examined six months and one year later. The work appears to have solved many of the problems that have existed since the buildings' erection and the perpetual spalling has ended.

Lyndhurst Gazebo, Tarrytown, New York

Historical Background:

Lyndhurst is one of many elaborate mansions built by the wealthy along the cliffs of the Hudson River during the nineteenth century. Overlooking the Tappan Zee bridge near Tarrytown, New York, Lyndhurst represents the culmination of Gothic Revival architecture in America. Commissioned to Alexander Jackson Davis (1803 - 1892) by William Paulding, a U.S. general and N.Y. major, in 1838, this was originally to serve as a retirement home.

George Merritt was the second owner and between 1864-65 he rehired Davis to extend the mansion to nearly double its original size. In addition, Merritt changed the name from Paulding Manor to Lyndhurst. Merritt died in 1873 and a new owner was not found until 1880 when Jay Gould, railroad magnate, bought the estate as a summer home.

This estate served the family until 1961. Jay Gould died in 1892 whereupon his daughter, Helen, later wife of Finley J. Shepard, inherited the property. Upon her death in 1938 her sister, Anna, Duchess of Talleyrand-Perigord, returned from France to live out her days at Lyndhurst. She died in 1961 and left the 67-acre estate to the National Trust for Historic Preservation.

The Goulds made extensive modifications to the property in their lifetimes, ranging from greenhouses and piers to kennels, a bowling alley, and a gazebo. Little is known of the stone gazebo situated west of the greenhouses (Figure 46). Estate records show that it was not there prior to 1939. It is presumed to have been purchased second-hand by the Duchess and brought to the estate around 1950.[28] Being continually exposed to the four seasons in an open area of the gardens, the gazebo had weathered considerably before the National Trust undertook its restoration in 1981.

Building Construction:

The gazebo, in construction and design, is typical of those for sale in mail-order catalogs popular during the late 1800s and onward. Although the origin of this structure is unknown, the pre-cast stone

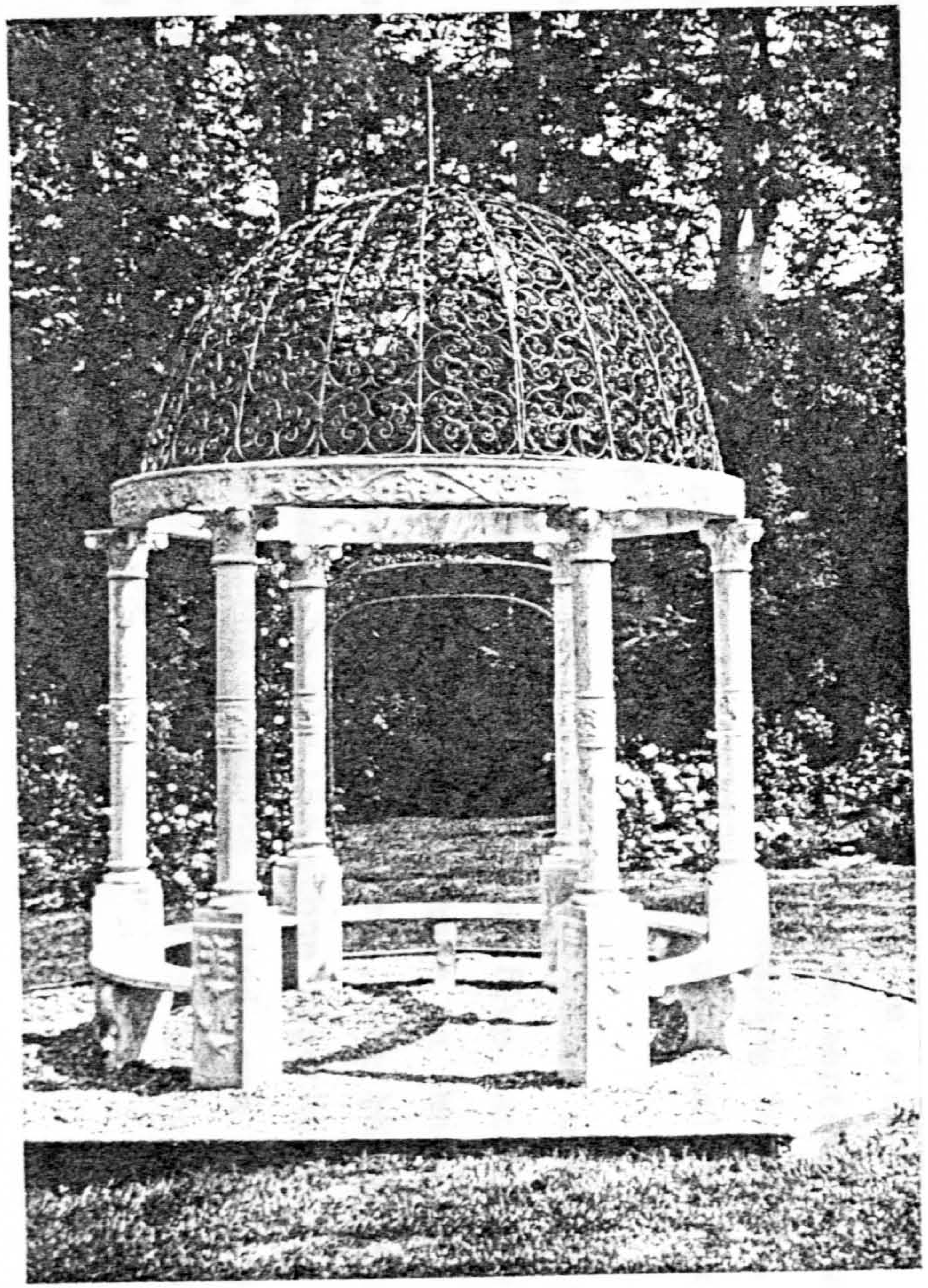


Figure 46: Lyndhurst Gazebo

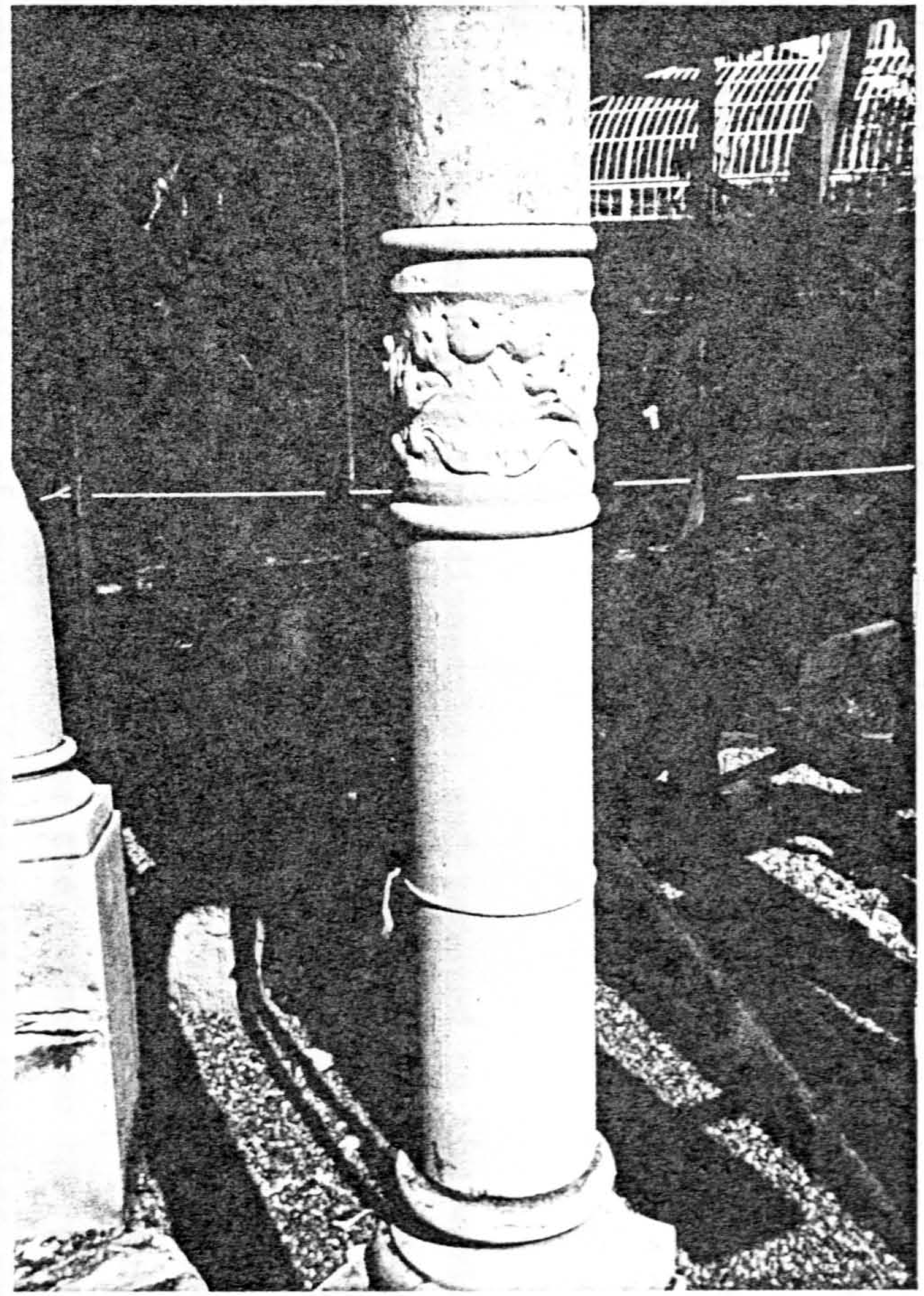


Figure 47

slabs locked into form with mortar and iron ties, and was covered with an elaborate iron cresting. It could well have arrived at Lyndhurst as a 'kit,' with instructions for assembling.

Until 1981 little repair work had been carried out. There were no records suggesting repairs and the general state of the gazebo by 1981 indicated that none was ever made. Considerable spalling had occurred where the iron ties had corroded and stained the stone.

Repairs:

In 1981 the structure was dismantled and removed to the workshop, near the greenhouses, for restoration. Originally the "plastic-stone" specifications for repair called for the use of STON-YL, a synthetic coating admixture, in the mortar mix for repairing the stone.[29] However, this was eliminated when discussion at the National Trust Workshop questioned its long-term stability and weathering effects.

The first step was to make moulds from the stones to be recast. Once completed, the pieces of each mould were clamped together and filled with a mix of 2:1 white Portland cement:fine sand. The mortar was then tamped to reduce shrinkage.

Once dry, the cast stone was removed and examined. Problems were immediately apparent. First of all, the texture was inappropriate, but more importantly, shrinkage had occurred, resulting in extensive cracking. The recasting began all over again and the mortar mix was changed to 3:1 white Portland cement:fine sand. Tamping followed. The changes brought success; the new stone matched the original in texture and color, and cracking was eliminated.

During reassembly, the stones were pinned into place using a mortar mix of 1:½:1:1 white Portland cement:hydrated lime:fine sand:limestone dust. The buttered joints were made flush to create an image of continuity, such as columns consisting of one piece, not three or more. All original galvanized iron, used to pin the stone together, particularly in the ring on which the cresting rested, was replaced with stainless steel. The steel pins were bedded in place using Sikadur "Hi-mod gel and Lo-Mod LV" epoxy.[30]

Observations:

The gazebo was visited in 1982 and 1983. On both occasions, the joints and the new cast stones had aged well with no cracks or crazing visible (Figure 47). The gazebo still retained a smooth surface, unpitted by the harsh rain, wind, and cold common in the region.

The Old North Church, Boston, Massachusetts

Historical Background:

The Old North Church, more formally known as Christ Church in Boston, was the second Church of England in Boston, Massachusetts (Figure 48). The first was a small wooden structure near the Boston Common. However as this busy seaport town grew, sea captains and merchants began to build north of town on a sea-washed peninsula called North End.

Initially, for a few years, the residents of North End continued to attend the church on the Boston green. But even this community began to expand, and soon a second place of worship became necessary. Subscriptions to the Church of England building fund for a new church began in 1722. By April of the following year enough funds had been acquired to allow construction to begin.

The selected site was next to the burial ground for the North End community in a pasture near the peak of Copp's Hill, the highest elevation in the North End. It was also near the 1715 home of Ebenezer Clough, one of the two masons who laid the brickwork of the church.

The Old North Church was 22 years under construction and upon completion, was one of the tallest buildings in the town. Although generally termed 'colonial' in style, it better depicts the English Baroque of the Wren churches in London.

This typical New England church became well known for the part it played at the start of the American Revolution. Robert Newman, the sexton, climbed into the steeple on April 18, 1775 and hung two lanterns there as a signal that a British force was moving up the Charles River to Cambridge. Newman had arranged with Paul Revere, a Boston silversmith, to hang lanterns based on the movement of the British, thus immortalizing the phrase, "one if by land, two if by sea." Revere, upon seeing the signal, rode to Lexington and Concord on horseback to warn the citizens that the British were coming. It is believed that skirmishes in Lexington and Concord the next morning, April 19th, set off the American Revolution.

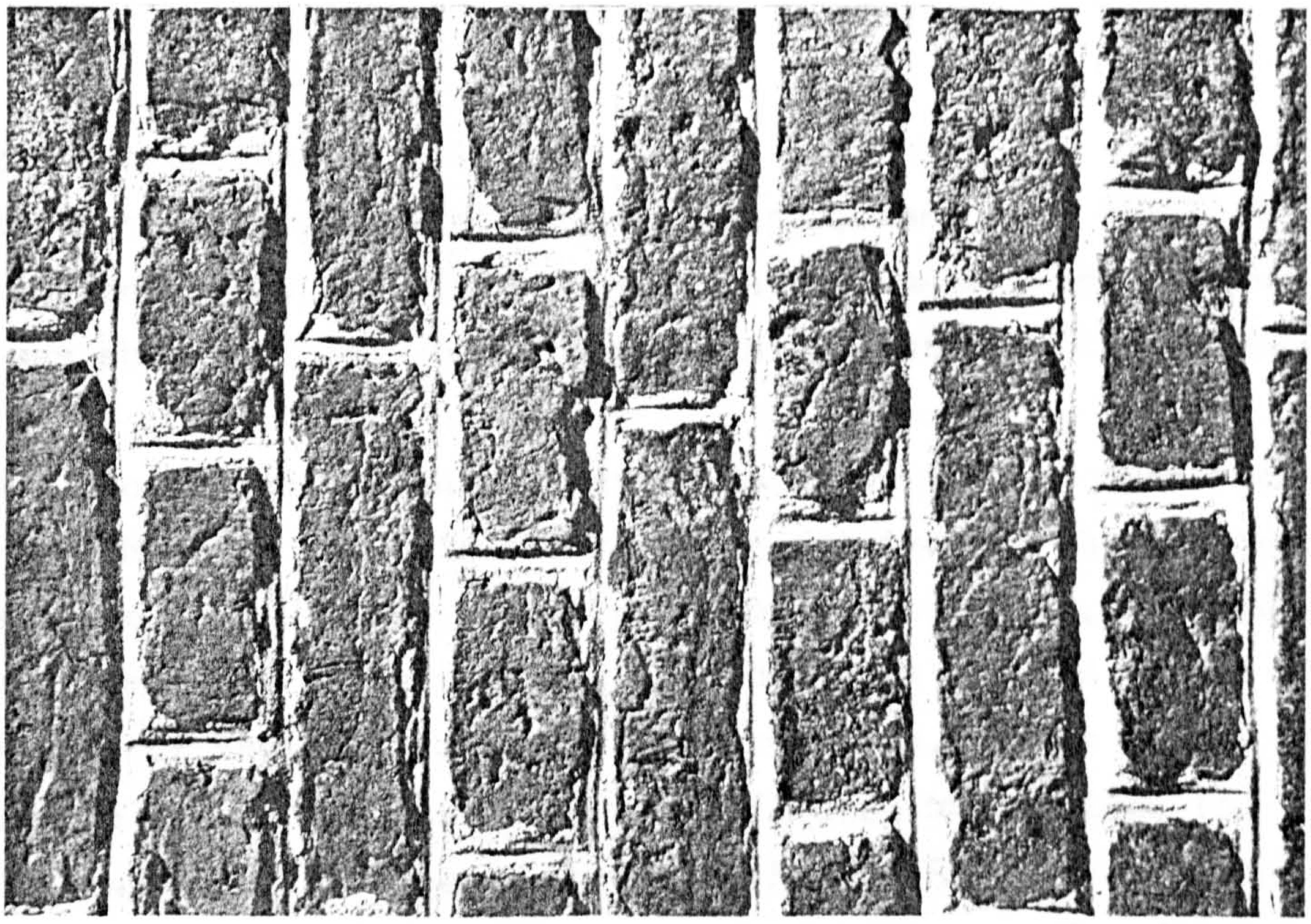


Figure 48.1

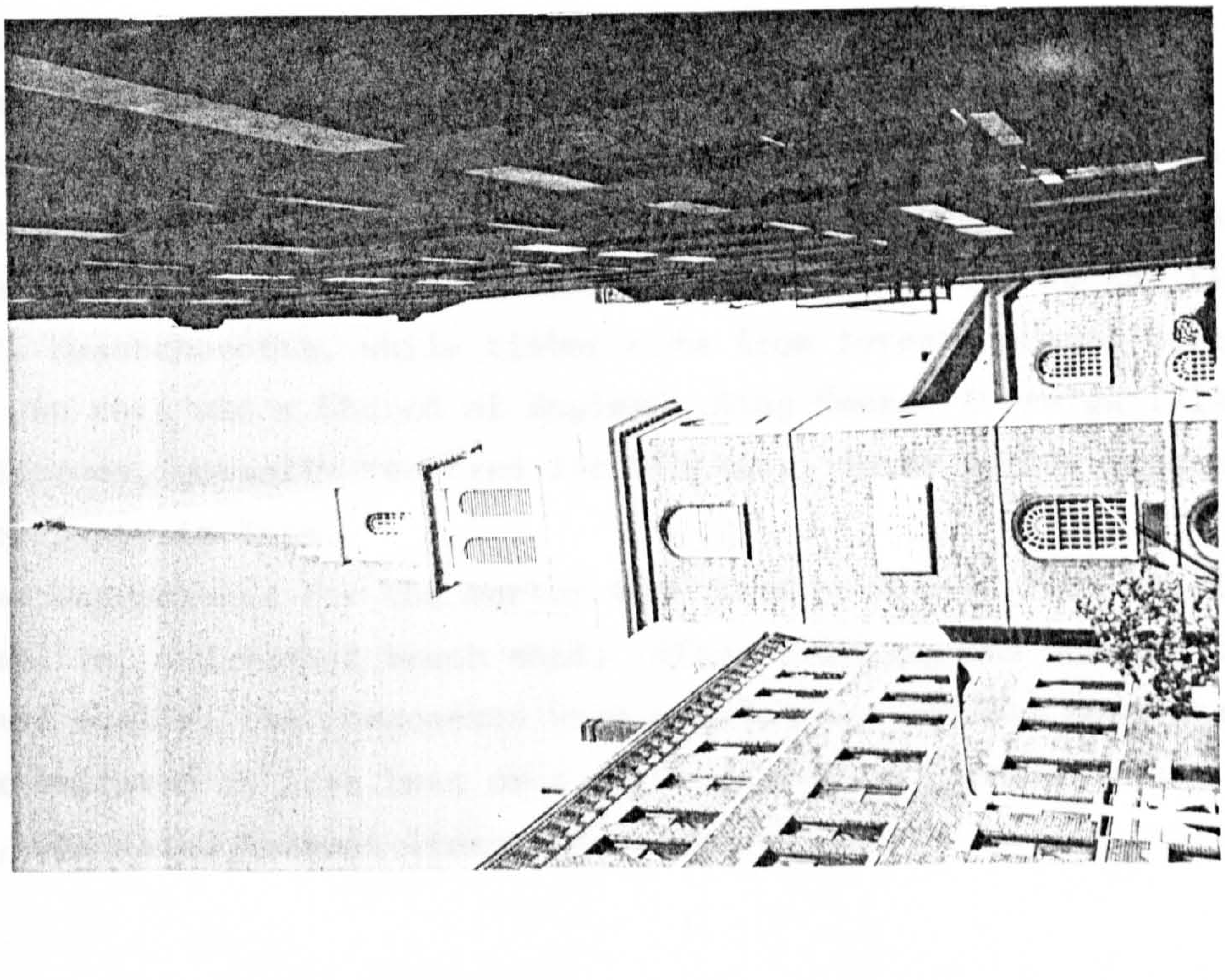


Figure 48: Old North Church

Since the Revolution, the Old North Church has continued to remain a small community church. Nevertheless, it has also been used as part of commemorative events, in particular the nation's Bicentennial in 1975 - 76.

Building Construction:

Despite the parishioners being colonists, they were still loyal British citizens when the Old North Church was under construction. This loyalty was shown not only through the design, but also in the materials used.

Oddly enough, no trained architect is known to have made plans for the church. Most of the original receipts survive for the construction of the edifice, and William Price, a Boston print dealer, is credited with having designed the structure. The builders erected one of the best examples of English architecture of the time. Their design was attributed to Sir Christopher Wren and reflected his designs for two of his London churches, St. James, Garlickhythe and St. Lawrence, Jewry. The brick portion of the Old North tower is similar to St. James in proportion, string courses, and window and door openings. The wooden steeple, on the other hand, was modeled after St. Lawrence.

Although it was not uncommon for the stone or brick ballast of ships to be used in building construction after making the Atlantic crossing, the materials used in the Old North Church were all of American origin. The building's facade was built of red brick laid in English Common bond, while the steeple and much of the interior was of wood and completed to Wren's designs. The bricks were made and fired in Medford, Massachusetts, while timber came from forests around York, Maine. As this was a Church of England, King George I (reign 1714 - 27) allowed trees, normally reserved for his Navy, to be felled from his crown property in York.

The ingredients for the mortar were limestone from Vermont, local beach shells, and washed beach sand. After crushing and burning the stone and shells, the components were worked to a useable consistency. The mix believed to have been used, according to a current vester of the church, was 1:1:3 Vermont limestone:shells:sand.[31]

After the cornerstone was laid by the Rev. Samuel Myles, rector of the first Church of England in Boston, in April of 1723, the church was under construction for 22 years (1723 - 45). The steeple was added in 1740. Upon completion the building measured 70 feet (21 m) in length, 51 feet (15-1/3 m) in breadth, and 42 feet (12-2/3 m) in height.

Later a vestry was constructed next to the church, behind the E. Clough house. These three building have remained intact since their construction with the exception of the church steeple. In 1804 the original steeple was destroyed. The Boston architect, Charles Bulfinch (1763 - 1844), redesigned one and within two years it was in place. It stood for 150 years before another hurricane again destroyed the steeple in the summer of 1954. A third steeple was designed from drawings of the original Wren-like spire and was constructed later that year.

Repairs:

Since its construction, the church has largely remained intact. This can be attributed to its historical significance and the desire of the congregation to retain the original features. At some time the pews were changed from boxes to rows, and once, during the nineteenth century, the exterior was painted gray. However in 1912, the Right Rev. William Lawrence, Bishop of Massachusetts, raised enough funds to have the entire structure restored to its original state. The box pews were restored, and the gray paint was removed by sandblasting.

During the 1930s additional work was carried out to upgrade the site and restore the grounds. In 1967 the church again underwent masonry repairs. Repointing on the exterior facades was performed under contract, and the original mortar mix was disregarded in favor of a 1:3 Portland cement:sand mix. This was applied to all joints after they had been raked out to a depth of ¼ - ½ inches (2/3 - 1¼ cm).

Observations:

The new mortar is gray in color, compared with the original reddish mortar. It was pushed into the shallow joints and slopped over onto the brick faces. The mason tried to strike or rule the joints with a trowel. The mortar has shown no visible signs of crazing or cracking, but rather has caused the arrises on the brick to chip (Figure 48.1).

The sandblasting did mar the brick considerably, and has caused the brick to weather at an accelerated rate over the years.

Conclusions

The above 19 case studies from Scotland and the United States were grouped into four categories based on the quantity of lime, with the cement proportion equal to 1. Originally the studies were classified by the formula: cement + lime to sand. This proved inadequate, however, as a mix of 1:2:9 would have been grouped with a 1:0:3, a much stronger mix without lime. The classification by lime content, where cement = 1, proved more suitable for drawing mutual or common conclusions for the case studies.

A classified summary of the mortar mixes is as follows:

No.	Case Study Name	Mortar Mix	
1	Craigmillar Castle	0:1:1:2	Arden lime:pebbles:sharp sand
		0:1:2-3	hydraulic lime:quarry sand
1	Edinburgh Castle	0:1:1:2	Arden lime:pebbles:sharp sand
		0:1:2-3	hydraulic lime:quarry sand
1	Fawside Castle	1:6 (1:4)	one part cement to six parts of a mix of 1:4 lime:sand (= 1:6:24)
1	Drayton Hall	1:4:8	white cement:lime:white sand
1	Schermerhorn Row	1:4:8	white cement:lime:sand (from 3 locations)
2	Inveraray Jails	1:2:9	cement:hydraulic lime: sand/gravel
2	Thirlestane Castle	1:2:9	cement:hydraulic lime:sand
2	Hermits & Termits	1:2:9	cement:lime:fine sand
		1:1 + 1:3	quicklime:veg oil + pigments
2	Buccleuch Church Wall	1:2:4:4	cement:hydraulic lime: concrete sand:building sand
3	Mylne's Court	1:1:6	cement:lime:sand
3	Public Theatre	1:1:6	cement:lime:sand

3	The Dairy	1:1:4½	cement:lime:sand
3	Ticknor-Campbell House	1:3	masonry mix:sand (like a 1:1:3)
4	Chapel of the Good Shepherd	1:½:4½	cement:lime:sand
4	The Belvedere	1:1/8:2½	cement:lime:sand
4	Quincy Market	1:½:4½	cement:lime:sand
4	Chesterwood	1:½:3	gray cement:lime:sand
		1:½:1½:3/8:¼:1	gray cement:lime:sand: marble chips:Dairy Clean: coal cinders & crushed coke
4	Lyndhurst Gazebo	1:½:1:1	white cement:lime:limestone dust:fine sand
4	Old North Church	1:0:3	cement:lime:sand

Age is the best determinant of how a building weathers. The above case studies range from 2 - 3 years up to 10 years. While two years may be considered young for a building to be examined, it should be noted that even at that age any initial cracks or crazing from early shrinkage, settlement, or other movement should have occurred.

Group #1: Lime/Cement >= 4

The studies classed in Group #1 had the highest ratio of lime to cement, and in two cases, were applied to old handmade bricks. In restoration work involving handmade bricks, it is important to remember that they have a low density as they were pressed into a mould by hand, not by machine. The outer crust is hard and dense due to the subsequent firing, but the interior remains porous and easily susceptible to rapid deterioration. H.J. McKee, in his book Introduction to Early American Masonry, repeatedly warns that the mortar should have the same density and absorbency as the stones or bricks. The greater the difference, the greater is the degree and rapidity of disintegration of the bricks.[32] This is substantiated by the British Building Research Station (now the Building Research Establishment or B.R.E.) in their

Digest 61: Strength of brickwork, blockwork and concrete walls. It indicates that a mortar mix should not exceed a 1:2:9 for a low density brick.[33]

In two of the studies, Edinburgh and Craigmillar Castles, the lime employed was hydraulic lime from France rather than hydrated lime. The use of hydraulic lime is not new: in the 1960s these two castles were repaired using Arden lime, a naturally-occurring hydraulic lime found in Scotland. When Ian Lindsay & Partners, Architects, first undertook the restoration of the nunnery on the isle of Iona, Scotland, they conducted tests on hydraulic and hydrated lime mortars to compare their elasticity and weatherability.[34] Hydraulic lime mortar appeared to be stronger, yet more plastic.[35] In other words, hydraulic lime mortar provided early strength and workability, yet had a greater tolerance for movement.

Both castles were recently repaired using a 0:1:2-3 hydraulic lime:quarry sand. Neither mix has developed cracks or crazing. The original repair at Thirlestane Castle, however, used a 0:1:3 hydraulic lime:sand, and this showed considerable shrinkage, resulting in its removal. Thus, shrinkage is worth further laboratory study.

The mortars employed in Group #1 have shown themselves to be of suitable density and absorption for the brick and stone involved.

Group #2: 2 <= Lime/Cement < 4

The four case studies classified as Group #2 were combined for their similar quantities of lime, and as in Group #1, this group contained case studies involving hydraulic lime.

At Thirlestane Castle, Ian Lindsay & Partners deviated from their normal procedures in the restoration of the keep. They still consulted the results from the tests on hydraulic and hydrated limes, but they chose a mortar mix devoid of cement. Originally they tried a mix of 0:1:3 hydraulic lime:sand, but the mortar proved to have a high shrinkage rate and created some crazing and spaces in the joints. They raked it out and replaced it with a 1:2:9 mix using hydraulic lime, and it has aged so far without any trace of cracks. There is evidence of crazing, but the B.R.E., in their Digest 200, states that as long as these fine cracks are less than 1.5 mm (1/16 inch) wide they can be ignored.[36] John Ashurst, in his book Mortars, Plasters and Renders in Conservation, suggests that crazing is the probable result of 1) shrinkage...due to rapid drying; 2) excessive early strength; or 3) dense impervious mix.[37]

Thirlestane served as an example for the other cases in this Group. Except for Hermits and Termits, the cases used hydraulic lime in the mortar mix from the beginning and have, with the one exception, had no problems. While hydraulic lime may show an increase in plasticity with strength, it appears to need some quantity of Portland cement to reduce its high shrinkage.

Group #3: $\frac{1}{2}$ < Lime/Cement < 2

The four case studies in Group #3 are typical of mortar mixes used in both the United States and the United Kingdom. The mixes chosen for the restorations were recommended by A.S.T.M. or by the B.R.E. In the case of Mylne's Court, the mortar chosen was based on published data from B.R.E. concerning that mix.

There is no particular conclusion to be drawn about these case studies other than a general one: that the repairs have shown no signs of deterioration as perhaps they should not if recommended by a governmental agency. The one exception is the 1973 repair at the Ticknor-Campbell house, repaired by the City of Ann Arbor, Michigan. One large patch near the southeast corner of the house has repeatedly been repaired, each time a large crack has reappeared. Selecting these cases allowed the governmental data mentioned above to be examined first-hand. Furthermore, they serve as a base line to the other case study groups.

Group #4: Lime/Cement <= $\frac{1}{2}$

The six case studies of this group, while containing various quantities of lime, do have one common factor: at some point in their lives, they were repaired with a mortar with a high Portland cement content. The Old North Church is classified in this group because the mortar mix used did not contain any lime. The use of a dense mortar without the plasticity obtained with the employment of a lime has been mentioned above by Harley McKee. Furthermore, observations and research made on the Group #4 studies indicate that either further repair has been necessary or damage to the surrounding materials has resulted.

Quincy Market and Faneuil Hall were repointed in the 1950s and 1960s, and today the walls show pitted bricks, cracks, and even joints with loose mortar. At Chesterwood, Mr. French continually mentioned stucco problems made from a cement mix. In the restoration of the Lyndhurst gazebo, the initial restoration mix of 2:1 cement:sand caused extensive shrinkage.

These cases indicate the need for lime in a mix, because the addition of lime helps to lower the density of a mortar and provide plasticity and retentivity.[38]

Summary:

These 19 case studies raise questions that require laboratory testing before thorough answers can be given. Each of the four groups demonstrate different aspects of wall behavior using a variety of mortar mixes. The first group, lime/cement >= 4, shows that mortars need to coexist with the surrounding building units; they should have a similar density and absorbency to the stones or bricks. This group also raises questions of shrinkage and shows the need for more information through laboratory testing.

The second group, 2 <= lime/cement < 4, also shows that shrinkage is an issue worthy of more investigation. More importantly, however, this series of studies shows the recent, increased use of hydraulic lime, not necessarily by itself as in Edinburgh or Craigmillar Castles in Group #1, but as an exact substitute for hydrated lime. In other words, the use of cement is not omitted, nor the quantity of lime reduced: a 1:2:9 mix can contain 2 parts of hydrated lime or 2 parts of hydraulic lime. This invites laboratory study to examine the pros and cons of using hydraulic or hydrated lime. Is creep higher? Or shrinkage lower?

The third group, $\frac{1}{2}$ < lime/cement < 2, consists of structures restored using governmental recommendations. These studies serve as checks and balances to the other studies based on the fact that these mortar mixes had previously been tested by governmental agencies. By retesting these, relationships can be drawn between the groups, and the previous test results can be checked.

The fourth and final group, lime/cement <= ½, gave examples where buildings were restored using dense mortars with a high content of Portland cement. Some damage was noted. This group serves as the opposite of Group #1: lime content was high there; here it is low. It also confirms McKee's statement that a mortar and the stones or bricks should have a similar density and absorbency, to minimize deterioration.

The issues of strength, shrinkage, and creep can be examined for all the 19 mortar mixes of these studies in a laboratory and the above raised questions answered. Pros and cons of one mortar mix over another can be studied.

References and Notes

1. S. Champion, Failure and Repair of Concrete Structures (New York: John Wiley & Sons, Inc., 1961).

2. A.P. Francis, "The Structural Repair of Mediaeval Masonry" (Society for the Protection of Ancient Buildings symposium: The Repair of Ancient Buildings, 19??), p. 5.

3. J.S. Richardson, Edinburgh Castle (Edinburgh: Her Majesty's Stationery Office, 1953), p. 9.

4. The term 'fireproof construction' unfortunately was not clarified or defined. W. Douglas Simpson, Craigmillar Castle (Edinburgh: Her Majesty's Stationery Office, 1980), 17.

5. David MacGibbon and Thomas Ross, The Castellated and Domestic Architecture of Scotland from the 12th to the 18th Century (Edinburgh: David Douglas, 1887), 409-13.

6. The Royal Commission on Ancient and Historical Monuments and Constructions of Scotland, The Eighth Report with Inventory of Monuments and Constructions in the County of East Lothian (Edinburgh: His Majesty's Stationery Office, 1924), 124.

7. Diane Maddex, ed., American Landmarks (Washington, D.C.: The Preservation Press, 1980), p. 55.

8. Pokorny states that this mix was altered very slightly on site in 1982, but that the change was negligible. Interview with Jan Pokorny, Jan Pokorny, Architects & Planners, New York, New York, December 1982.

9. Ian G. Lindsay and Mary Cosh, Inveraray and the Dukes of Argyll (Edinburgh: Edinburgh University Press, 1973), p. 315.

10. Lindsay, Inveraray, 316.

11. Lindsay, Inveraray, 318.

12. Lindsay, Inveraray, 319.

13. Interview with Crichton Lang, Ian Lindsay & Partners, Architects, Edinburgh, Scotland, November 11, 1982.

14. Benjamin Tindall, "Hermits and Termits" (unpublished architectural report), 1981.

15. The harling was analyzed November 27, 1981 by the author in

the laboratory in the Department of Architecture at the University.

16. Edinburgh Public Library, Edinburgh Room, Boog Watson Notes, vol. 5, 1820, p. 42.

17. Interview with mason, Orbit Builders, Linlithgow, Scotland, July 24, 1981.

18. Interview with Angus Robertson, T. Harley Haddow, Engineers, Edinburgh, Scotland, November 11, 1982. The three mixes with available stress data are 1:1:6, 1:2:9, and 1:3:12 cement:lime:sand.

19. Olaf Shelgren; Cary Lattin; and Robert Frasch, Cobblestone Landmarks of New York State (Syracuse: Syracuse University Press, 1978), p. 9.

Cement and mortar were words used to describe the same building materials. It was not until Portland cement and other stronger forms of mortar were invented that these words began to acquire different meanings.

The phrase, lime in the stone, means limestone after burning, but before grinding or pulverizing.

20. Shelgren, p. 19.

21. Shelgren, pp. 19 - 20.

22. Mrs. Nan P. Hodges, Cobblestone Farm Association, letter of May 20, 1981.

23. Hodges.

24. The American Architect & Building News, v.26, n.27, July 20, 1889.

25. The restoration mortar was pigmented, but the specifications did not state what the pigment was. Cavaglieri mentioned that he used brick dust. Interview with Giorgio Cavaglieri, Giorgio Cavaglieri, Architect, New York, New York, April 14, 1981.

26. The Type N mortar defined above was taken from ASTM C-270. Oddly enough, this differs slightly from the Type N mortar defined by Benjamin Thompson, Architects, in their specifications for Quincy market.

27. Arthur Dutil of the National Trust believes that the materials, coal cinders, and marble dust, may have been taken from the railroad beds in Stockbridge. Bits of nails and glass can be found in the original stucco, matching materials found on the local railroad beds. Interview with Arthur Dutil, The National Trust for Historic Preservation, Stockbridge, Massachusetts, August 17, 1982.

28. Interview with Allan Keiser, Restoration Workshop Director, The National Trust for Historic Preservation, Tarrytown, New York, April 7, 1981.

29. Mr. Keiser did not state the property that STON-YL would impart, nor where it was manufactured.

30. In the gazebo columns, 1" dia. x 6" (2½ x 15 cm) stainless steel pins were used. In the ring, resting on the columns, ¼" dia. x 4" (2/3 x 10 cm) pins were employed.

Sikadur is an epoxy manufactured by Sika Chem of New Jersey.

31. Interview with Albert Mostone, Contractor, and Vester for Old North Church, Boston, Massachusetts, May 17, 1981.

32. Harley J. McKee, Introduction of Early American Masonry (Washington, D.C.: National Trust for Historic Preservation, 1973), pp. 56, 72, 73.

33. Building Research Station, Strength of brickwork, blockwork and concrete walls, Building Research Station Digest 61 (London: Her Majesty's Stationery Office, 1965), p. 2.

34. Ian Lindsay & Partners often work in conjunction with T. Harley Haddow, Engineers. Angus Robertson, associated with the latter, states that a 1:1:6, 1:2:9 or 1:3:12 mortar mix is always recommended as stress figures, etc. are already available for these mixes, and thus, these firms will have an idea how the mortar will age over time. All Lindsay & Partners did was substitute one material for another. Interview with Angus Robertson, T. Harley Haddow, Edinburgh, Scotland, November 11, 1982. Interview with Crichton Lang, Ian Lindsay & Partners, Architects, Edinburgh, Scotland, November 11, 1982.

35. Interview with Crichton Lang, November 1980.

36. Building Research Establishment, Repairing brickwork, Building Research Establishment Digest 200 (London: Her Majesty's Stationery Office, 1977), p. 6.

37. John Ashurst, Mortars, Plasters and Renders in Conservation (London: Ecclesiastical Architects' and Surveyors' Association, 1983), p. 24.

38. See Chapter 5 for a discussion of the properties of lime and cement.

Chapter 5: The Behavior of Mortars in Masonry

Introduction

In traditional building techniques, mortars were made to perform a three-fold function. They were employed to bond together stone or brick units and aid them in resisting lateral forces. They served to seal all joints against weather penetration. They provided an even bed for the units, thus allowing loads to be evenly distributed throughout the wall.[1]

Some traditional building materials and methods were supplanted by modern building techniques introduced around 1880. Hardened brick, concrete masonry units, and Portland cement mortar have been increasingly used in new masonry construction since the late nineteenth century. When older structures have needed repair, new materials have been used to make the repairs. This has led to situations where, for example, a dense mortar of high cement content is used in repointing early nineteenth century walls of handmade brick. Architects, contractors, and masons have found that such a combination does not always produce a satisfactory repair. Indeed, some of the case studies considered (e.g. Ticknor-Campbell House and Old North Church) have shown that cement-rich mortars have developed severe cracks and caused damage to the masonry units. Other case studies (e.g. Drayton Hall and Thirlestane Castle) have demonstrated that lime-rich mortars have produced satisfactory repairs, at least during the time of observation.

The observed behavior of both new and old mortars raises questions concerning the nature of various mortars and their abilities, in a masonry wall, to respond to various stresses and movements. Case study evidence suggests that weaker, softer, less dense, lime-rich mortars may tolerate certain stresses and movements better than stronger, harder, more dense, cement-rich mortars. Before investigating that tolerance, the nature of the various stresses and movements in masonry walls will be examined.

Definitions

Compression: A state of stress in which the particles of a material are pushed one against the other, thus tending to shorten it.

Creep: The slow strain in a loaded material in addition to the elastic or instantaneous strain. It is a gradually increasing viscous deformation calculated by subtracting the instantaneous strain from the total strain.

Creep Recovery: The slow recovery of deformation which follows elastic recovery.

Drying Shrinkage: The irreversible deformation of mortar during drying after first setting.

Elastic Deformation: The deformation of a material under load, which is recovered when the load is removed.

Elastic Recovery: The strain recovered on removal of load. In laboratory experiments, the elastic recovery is approximated by the recovery measured during an arbitrary short time; in this study the time is defined as one minute.

Elastic Strain: The strain, caused by an applied stress, that may be recovered when the stress is removed. In laboratory experiments, the elastic strain is approximated by the strain measured during an arbitrary short time; in this study the time is defined as one minute.

Load: A force applied to a body of material.

Modulus of Elasticity (also termed 'Young's modulus'): The ratio of stress to strain, which is constant until the stress reaches the yield point.

Plastic Deformation: Any deformation of a material under load, which is not recovered when the load is removed.

Plastic Strain: The strain, caused by an applied stress, that is not recovered when the stress is removed.

Shear: A state of stress in which the material is subject to opposite stresses not in the same line of action, and in which one plane tends to slide across an adjacent plane.

Strain: A measure of the deformation of a member caused by an applied stress, calculated by dividing the change of length at a given time by the original length.

Strain Ratio: The ratio of maximum strain (instantaneous and creep) to instantaneous strain.

Stress: The force in a member divided by the area which carries the force, expressed in N/mm^2.

Tension: A state of stress in which the particles of a material tend to be pulled apart, thus tending to elongate it.

Yield Point: The stress at which a material starts deforming rapidly in a clearly plastic fashion.

Masonry Wall Behavior

Observable behavior of masonry walls results from movements of both external and internal origin. Movements tend to cause stresses within the structure, which result in strain or deformation of the materials. While each single masonry material may have well known physical properties, the combination of materials in a wall may make behavior of the wall complex.

Some movements are caused by internal changes of masonry materials. Drying shrinkage is a permanent, non-reversible movement of a material such as concrete or mortar. Prepared as a wet, workable substance, mortar shrinks as it dries and hardens, regardless of whether it is within a masonry wall or out in the open. Drying shrinkage is by far the most significant permanent internal movement; movements from such other causes as carbonation, a chemical change in cement-based materials, are minor in comparison.[2]

While drying shrinkage occurs in the early life of mortars and hence masonry walls, significant movements can result from environmental changes of moisture and temperature throughout the life of the wall. These are still internal movements of masonry materials, but caused by external elements. Wet/dry cycles, as caused by periods of wet and dry weather, can make masonry expand and contract considerably. Weather changes also cause cycles of heat and cold. Each material has inherent thermal properties that cause it to expand with a temperature increase. Table 10 lists various building materials and their thermal coefficients. Thermal behavior is also dependent on such qualities as color: darker materials absorb more direct solar radiation than light materials. In a built structure made of more than one material, the different shrinkage, thermal, and moisture movements of each material interact.

External movements, on the other hand, are those transmitted to the masonry by strictly external forces. The differential movements of a structure's supports, as during settlement, induce complex movements and distortion. Horizontal forces, such as wind, must be resisted, though these are usually minor. The major, intended force resisted by masonry walls is gravity. Obviously, load-bearing masonry must properly carry applied weight loads to be useful. Weight loads include constant dead loads, and variable live loads. Because masonry materials are most useful in compression (they have low tensile and shear strength), their behavior under applied weight loads is important.

Masonry structures are not totally free to move as much as their

Material	Coefficient x 10^6 °C	°F
Ashlar masonry		3.5
Brick masonry		3.4
Rubble masonry		3.5
Bricks	5.0	2.8 - 4.0
Clay brickwork	5.0 - 8.0	
Calcium silicate brick	8.0 - 14.0	
Aggregate concrete block	6.0 - 12.0	
Aerated concrete block	8.0	
Lime mortar	8.0 - 10.0	4.1 - 5.1
Cement mortar	10.0 - 11.0	3.2 - 8.1
Portland cement		7.0
Structural clay tile		3.3
Concrete	10.0	6.5
Reinforced concrete	7.0 - 14.0	
Granite	8.0	4.0
Limestone	7.0	3.8
Marble	8.0	5.6
Plaster		9.2
Sandstone		4.4
Steel	11.0	6.7
Stainless Steel	14.0	9.9
Aluminum	23.0	12.80

Table 10: Coefficient for Thermal Expansion for Some Building Materials.

physical characteristics or external forces would dictate. It is the restraint of movements that results in stresses. For example, when dissimilar materials are firmly attached to each other, a changing environment (thermal or moisture) will cause stress because each material will restrain the other. Often in real structures movements are not totally restrained, but rather a balance of some movement and some restraint results.[3]

When movement is restrained, stresses of three types may develop: compression, tension, and shear. Generally, masonry structures are in a state of compression because of the weight loads they support. But tension and shear can also result from such movements as settlement. Cracks often result from tension.

Stresses can be minimized by purposefully providing for movement where restraint might result in severe damage. Expansion joints allow expansion and contraction to occur in long structures where the lengths involved would multiply differential thermal effects. Common locations for these joints are the intersections of wings to a main structure, where new buildings abut older ones, or at corners where expansion in two directions tend to push the walls outward. Equally important sites are exterior building elements such as parapet copings whose length might be especially affected by thermal movement. The width of an expansion joint in modern building construction is generally defined as one inch (2.5 cm); however, the actual amount a material will expand, given a particular situation, should be calculated.[4] The formula for this is as follows: "Multiply span of material x 100^{o}F (average difference in temperature between summer and winter, or 55^{o}C) x the coefficient of thermal expansion of the material."[5]

Following the translation of movements to stresses in masonry, the stresses translate to observed physical results. The result is deformation, a physical change of dimension of the material. Deformation measured on a per-unit-length basis is strain. Just as each material shows particular thermal and moisture behavior, each shows a certain behavior (strain) as a response to stress. The stress/strain ratio, called Young's Modulus or the modulus of elasticity, of several materials is given in Table 11. The modulus is considered constant

Description of Materials			Stress/Strain Relationship psi x 10^6	N/mm^2 x 10^4
Bricks in cement mortar based on brick strength:				
1500 - 3000 psi	(10.34 - 20.69 N/mm^2)		0.29 - 1.02	0.20 - 0.70
3000 - 5000	(20.69 - 34.48)		0.61 - 1.21	0.42 - 0.83
5000 - 7000	(34.48 - 48.27)		0.93 - 2.34	0.64 - 1.61
7000 - 10,000	(48.27 - 68.96)		1.39 - 2.66	0.95 - 1.83
over 10,000	(over 68.96)		2.49 - 3.59	1.71 - 2.47
Bricks in non-hydraulic lime mortar based on brick strength:				
2480 psi	(17.10)		0.193	0.13
3060	(21.10)		0.104	0.07
5500	(37.93)		0.160	0.11
Bricks in hydraulic lime mortar based on brick strength:				
8340 psi	(57.52)		1.22 - 1.52	0.84 - 1.05
Bricks in cement-lime mortar with brick strength: 2940 psi (20.27)				
--in 1:1:6 mortar			1.70	1.17
--in 1:2:9 mortar			1.50	1.03
--in 1:3:12 mortar			1.20	0.83
Hollow clay blocks in cement mortar based on block strength and approx. size:				
9 x 4 x 6	1430 psi	(9.86)	1.37	0.94
12 x 3 x 8	1326	(9.14)	1.98	1.36
9 x 4 x 9	935	(6.45)	2.75	1.89
12 x 3 x 9	363	(2.50)	0.47	0.32
12 x 4 x 9	246	(1.69)	0.42	0.29
12 x 2-1/2 x 9	354	(2.44)	0.50	0.34
9 x 8-1/2 x 8-1/2	923	(6.36)	0.64	0.44
Hollow clay blocks in cement-lime mortar based on block strength at 28 days:				
550 - 1140 psi	(3.79 - 7.86)		0.30 - 1.17	0.21 - 0.81

Table 11: Modulus of Elasticity for Some Building Materials.

Taken from: R. Fitzmaurice, Principles of Modern Building, v. 1 (London: His Majesty's Stationery Office, 1949), p. 129.

until the elastic yield point is reached.

Deformation occurs in two forms, elastic and plastic. Elastic deformation is that which is readily recovered when the stress is removed, as, for example, in the case of a wall that is compressed by an applied load and regains its shape when the load is removed. Plastic deformation is that which is permanent and not immediately recovered upon removal of the stress. Usually, the deformation caused by an applied load on a masonry wall is not totally recovered if the load is removed. Thus, most deformation under load is part elastic and part plastic.

Creep is an important kind of plastic deformation of masonry structures. Masonry materials under weight load--e.g. in compression--exhibit plastic deformation which gradually increases with time, but at a decreasing rate. Creep of mortars and other materials allows them to tolerate some movements without damage. Tolerance of movement by each material contributes to the tolerance of movement by the entire masonry structure.

Figure 49 illustrates graphically the difference between creep and other strains. At t=0 the freshly prepared mortar begins shrinking even though not under load; strain rises from zero. A load is applied at $t=t_1$, resulting in an instantaneous strain, the magnitude of which is determined by the amount of load and modulus of elasticity of the mortar. This strain is, theoretically, elastic; in laboratory experiments the amount is measured during an arbitrary time of one minute under load.[6]

Further strain--creep--occurs after loading at a gradually decreasing rate under load, until the load is removed at $t=t_2$. The elastic strain, theoretically totally and instantly recoverable, is measured in the laboratory during an arbitrary time period of one minute after the load is removed. Thereafter, a small fraction of the creep will be gradually recovered, and the mortar will continue to shrink until it is completely dry.

Creep and other deformations occur only as far as the masonry's strength will allow. Increasing loads beyond load-bearing capacity will obviously crush a wall. Failure of a material results when stress

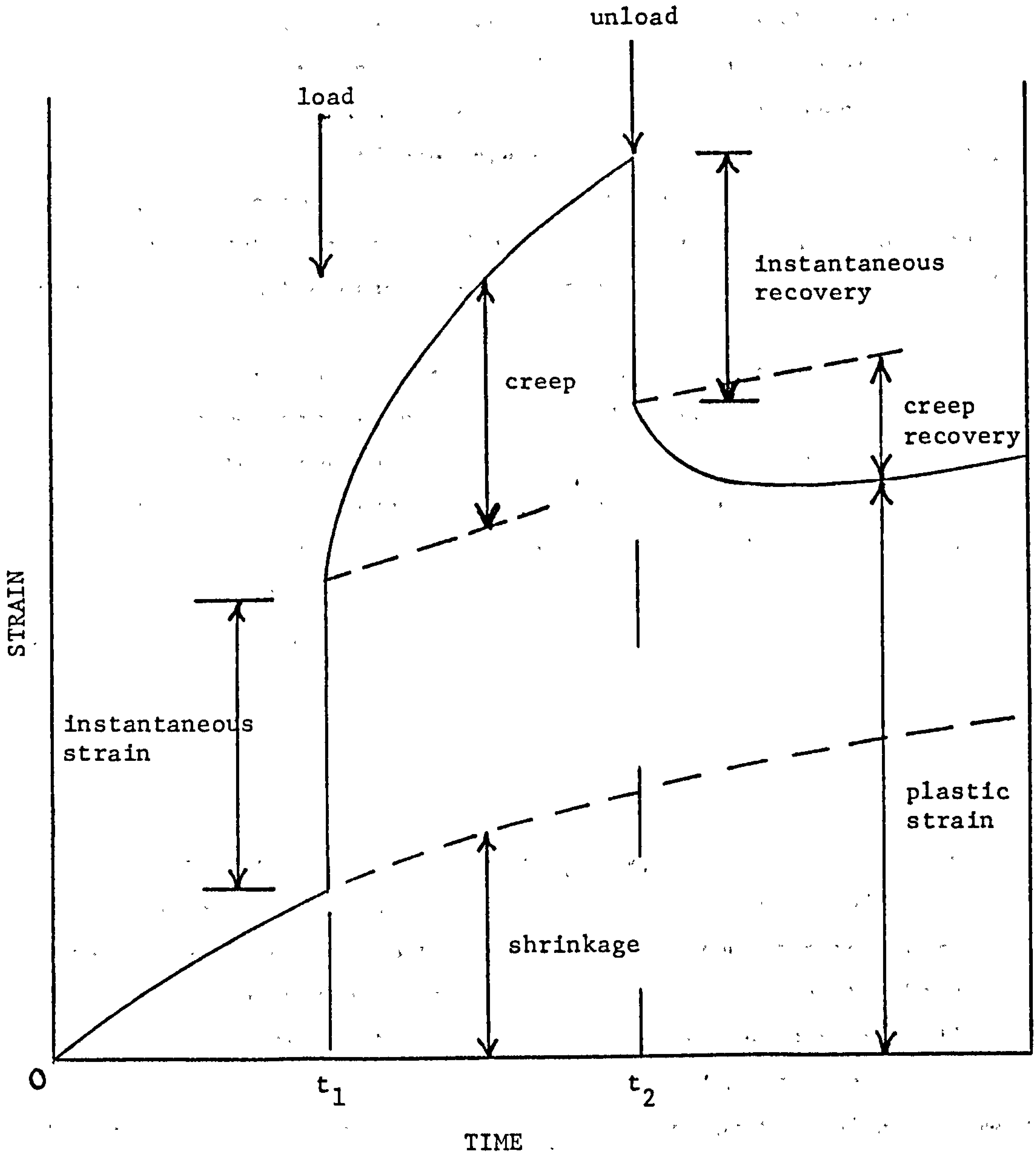


Figure 49 : Reactions of Mortars Before, During, and After a Load is Applied.

Modified and Taken from: Cement & Concrete Association, Training course note TDH8302.

exceeds the material's yield point; a wall will fail when the yield point of its weakest material is exceeded. On a microscopic scale, however, small failures can occur even if the wall stands. For example, settlement of one wall section may cause failure in shear and tension along a boundary between the area of stablility and the area of settlement, creating visible, gross cracks. Uneven loads could also result in cracking in affected areas. Gross cracks may admit dirt, moisture, and biological organisms into the masonry's interior, accellerating deterioration. Clearly a mortar developing numerous tiny, practically invisible cracks is preferable to it developing a few large cracks.

One of the primary functions of mortar is to distribute loads evenly within masonry structures. The ideal mortar performs this first by conforming to irregularities during construction, and then by undergoing plastic deformation during the life of the structure in order to tolerate movements caused by heat, cold, wet, dry, and various loads. However, it is not obvious exactly which mortar would be ideal in a particular situation.

Mortar Mixes

According to the results of one study, 60 - 80% of the total deformation of a loaded wall takes place in the mortar bed joints. Between 20 - 40% of the combined elastic and creep strain occurs in the bricks. Bearing in mind that bricks account for 85% of the height of the wall, it follows that the strain in the bricks is very small relative to that in the mortar.[7] This fact emphasizes the importance of mortar in wall behavior. The properties of a good mortar are cohesiveness, adhesiveness, strength, setting time, hardening time, handling ease, and ability to set and harden under water (hydraulic quality).[8]

Besides these characteristics, it is important for a mortar to 'fit its environment.' Past experience in both the built environment and in the laboratory has shown that the greater the difference between the mortar and the unit in properties such as density, thermal expansion, and absorbency, the greater is the degree of deterioration.[9] An unnecessarily strong mortar concentrates the effects of any differential movement in fewer and wider cracks; a weaker mortar will accommodate smaller movements and any cracking will be distributed as hair cracks in the joints. The stresses resulting from restraint of any expansion of bricks are reduced if a relatively soft mortar is used.[10]

British Standard Code of Practice #121 states that "visible cracking may be reduced by the suitable choice of mortar."[11] The Building Research Establishment suggests "that the mortar used should contain no more cement than is necessary to give adequate strength in the brickwork."[12] Both organizations have published elaborate charts on the mortar mixes to use in various parts of a building. These are reproduced in Tables 12 & 13. It is interesting to note that all mortar groups contain a quantity of lime or a substitute plasticiser, thus increasing the workability of the mortar and reducing the strength relative to that of a neat cement mortar.

The British Limestone Federation have also studied mortars and conclude that lime and Portland cement are both important constituents of a mortar. The lime confers:

(i) good working qualities
(ii) good water retentivity
(iii) freedom from major cracking
(iv) slow hardening with good final strength
(v) marked advantages in appearance

while cement, added to the lime, gives:

(vi) higher early strength
(vii) increased durability in adverse conditions.[13]

The Lime Federation's statement that both lime and cement are necessary in a mix is all well and good, but it creates the need to determine how much of each product, mixed with sand, is required to produce a mortar with the qualities first stated above. The charts put out by the Building Research Establishment and British Standards describe suitable locations for various mixes, but they do not give reasons for their choices. Some scientists have studied creep in order

Table 12. Selection of mortar groups

Type of brick:	Clay		Concrete and calcium silicate	
Early frost hazard[a]	no	yes	no	yes
Internal walls	(v)	(iii) or (iv)[b]	(v)[c]	(iii) or plast(iv)[b]
Inner leaf of cavity walls	(v)	(iii) or (iv)[b]	(v)[c]	(iii) or plast(iv)[b]
Backing to external solid walls	(iv)	(iii) or (iv)[b]	(iv)	(iii) or plast(iv)[b]
External walls; outer leaf of cavity walls:				
—above damp-proof course	(iv)[d]	(iii)[d]	(iv)	(iii)
—below damp-proof course	(iii)[e]	(iii)[b, e]	(iii)[e]	(iii)[e]
Parapet walls; domestic chimneys:				
—rendered	(iii)[f, g]	(iii)[f, g]	(iv)	(iii)
—not rendered	(ii)[h] or (iii)	(i)	(iii)	(iii)
External free-standing walls	(iii)	(iii)[b]	(iii)	(iii)
Sills; copings	(i)	(i)	(ii)	(ii)
Earth-retaining walls (back-filled with free-draining material)	(i)	(i)	(ii)[e]	(ii)[e]

a during construction, before mortar has hardened (say 7 days after laying) or before the wall is completed and protected against the entry of rain at the top

b if the bricks are to be laid wet, *see* 'Cold weather bricklaying'

c if not plastered, use group (iv)

d if to be rendered, use group (iii) mortar made with sulphate-resisting cement

e if sulphates are present in the groundwater, use sulphate-resisting cement

f parapet walls of clay units should not be rendered on both sides; if this is unavoidable, select mortar as though *not* rendered.

g use sulphate-resisting cement

h with 'special' quality bricks, or with bricks that contain appreciable quantities of soluble sulphates.

Table 12: Selection of Mortar Groups

Taken from: Building Research Establishment, "Mortars for bricklaying," Building Research Establishment Digest 160 (London: Her Majesty's Stationery Office, 1973), p. 2.

Table 13 Mortar mixes (proportions by volume)

	Mortar group	Cement : lime : sand	Masonry-cement : sand	Cement : sand, with plasticiser
Increasing strength but decreasing ability to accommodate movements caused by settlement, shrinkage, etc ↑	i	1 : 0–¼ : 3	—	—
	ii	1 : ½ : 4–4½	1 : 2½–3½	1 : 3–4
	iii	1 : 1 : 5–6	1 : 4–5	1 : 5–6
	iv	1 : 2 : 8–9	1 : 5½–6½	1 : 7–8
	v	1 : 3 : 10–12	1 : 6½–7	1 : 8
Direction of changes in properties		← equivalent strengths within each group →		
		increasing frost resistance →		
		← improving bond and resistance to rain penetration		

Where a range of sand contents is given, the larger quantity should be used for sand that is well graded and the smaller for coarse or uniformly fine sand.

Because damp sands bulk, the volume of damp sand used may need to be increased. For cement: lime: sand mixes, the error due to bulking is reduced if the mortar is prepared from lime: sand coarse stuff and cement in appropriate proportions; in these mixes 'lime' refers to non-hydraulic or semi-hydraulic lime and the proportions given are for lime putty. If hydrated lime is batched dry, the volume may be increased by up to 50 per cent to get adequate workability.

Table 13: Mortar Mixes

Taken from: Building Research Establishment, "Mortars for bricklaying," Building Research Establishment Digest 160 (London: Her Majesty's Stationery Office, 1973), p. 3.

to better understand the behavior of masonry structures.

Present Creep Knowledge

Creep is a plastic deformation caused by applied stress. The amount of creep in masonry is determined by the materials used, particularly the mortar.[14] Considerable research has been carried out on creep of concrete, and also creep of brickwork and blockwork built with cement mortar. D. Lenczner and A. Neville are two of the active investigators in this field.

Comparative creep tests have been made on walls and piers. Lenczner found that the geometry of a brickwork member greatly affected its creep. Creep was greater in walls than in columns, greater in hollow piers than in cavity walls, greater in single leaf walls than in cavity walls, and greater the taller the column.[15] Blockwork piers underwent greater creep than brickwork piers.[16] With a stress magnitude of 0.5 - 1 N/mm^2, strain ratios for brickwork and blockwork cavity walls were in the range of 2 - 2.4, but single leaf brick walls were in the range of 3 - 4. Both the instantaneous and creep strains in the bricks themselves were considerably smaller than in the wall as a whole. This was compensated by correspondingly greater strains in the mortar joints.[17]

A 1:¼:3 and a 1:1:6 Portland cement:hydrated lime:sand were commonly-used mixes employed in Lenczner's testing program. They, along with masonry geometry, affected the amount of creep experienced. Piers were tested, and the results showed that piers built with the weaker mix had creep strains 2 - 3 times larger than piers built with the stronger mortar.[18] Creep also continued longer with the weaker mix.[19]

The rate of creep also varied depending on the masonry geometry and mortar employed. In brickwork walls, the creep strain increased rapidly initially, then slowed down progressively with time, but continued for 261 days.[20] Lenczner did note, however, that at higher stress levels, secondary creep set in after approximately 80 days and continued at an increased rate.[21]

Neville studied the creep of concrete made with ordinary Portland cement, gravel, and fine aggregate. He suggested that both fineness of cement and its strength affected creep, and specifically that creep was inversely proportional to the strength of concrete at the time of load application.[22] The age at which a load was applied greatly affected the magnitude of creep; this fact resulting from the increase of concrete strength with age.[23] Neville further linked creep to shrinkage. For low stresses, concrete deformation was equal to shrinkage or was no greater than shrinkage of an unloaded specimen.[24] (Shrinkage is important, but little data have been published. Most scientists record shrinkage data as a control measurement in the experimental program, but few write it up as it was not the issue being studied.[25])

The studies conducted by Neville and Lenczner have shown that creep, unlike shrinkage, may relieve stress concentrations induced by shrinkage and temperature changes.[26] Creep reduces internal stresses due to non-uniform deformation, thus reducing cracking. The programs studied largely dealt with entire walls or piers, not just mortar. But the results have shown that the mortar mix does influence the quantity of creep experienced. (Some of Lenczner's experiments on brickwork piers did show that the type of brick and the presence of a damp-proof course also affected creep.[27])

The published data suggested a further experimental program on creep in mortar alone. Such a program would compare the creep of a number of mortars with different proportions of lime and cement under stress of a magnitude likely to occur in walls of buildings.

Creep Testing

Lenczner and Neville's published findings provide the background of relevant knowledge on which the present author's program of mortar testing was designed.[28]

All previous laboratory research on creep has, whenever possible, been conducted under a strictly controlled environment using standard equipment each time. One reason for this was to produce consistent creep data. For example, Lenczner noted that the creep of a specimen of concrete at 50% relative humidity could be 2 - 3 times greater than creep at 100% R.H.[29] By maintaining a constant relative humidity and temperature, such variation was eliminated.

During experiments published by Neville in September 1977, concrete samples were cured in water at 22 +/- 2°C (71.5 +/- 3.5° F) from the age of one day to 28 days. Thereafter if the samples were stored in air, the temperature remained the same and the relative humidity was constant at 60 +/- 7%. The concrete was loaded at the ages of 28 and 56 days for periods of up to 84 days, then unloaded and allowed to recover.[30] Similar procedures are used by Lenczner.[31] Both men have worked with 2" diameter x 9¼" long (5 cm x 23-1/8 cm) sample cylinders, although Neville sometimes used 76 mm diameter x 255 mm (approximately 3" x 10") cylinders.[32] In all cases, controls were maintained on each different sample, and corresponding 3" (7½ cm) cubes have been used to determine compressive or crushing strength.

The creep machine used to test mortar or concrete cylinders is designed on the nutcracker principle and was first employed by Ross.[33] Neville and Lenczner have each altered the original form. Neville applied a load by putting a steel rod under tension and then measured the load by calibrating the rod's extension against a proving ring placed where the sample cylinder had been. Lenczner chose, instead, to use proving rings in place of the steel rod as the sensitivity of the rings was greater.[34] See Figure49.1for a visual comparison of Neville's and Lenczner's machines.

Once the laboratory itself was controlled and equipment in place, Lenczner and Neville began tests on creep in brick- and block-work piers and walls. Experiments conducted by Lenczner have dealt with two specific mortar mixes: 1:¼:3 and 1:1:6. In 1970 he studied the effects these two mixes had on brickwork piers.[35] Simultaneously, Lenczner recorded the compressive strength of these mixes by crushing 3" (7½ cm) mortar cubes at 7 and 28 days. On the 28th day the piers were loaded. Those with 1:¼:3 mortar were loaded at stress levels ranging from 247 to 870 lbf/in^2 (1.7 to 6.0 N/mm^2); those with 1:1:6 were loaded at

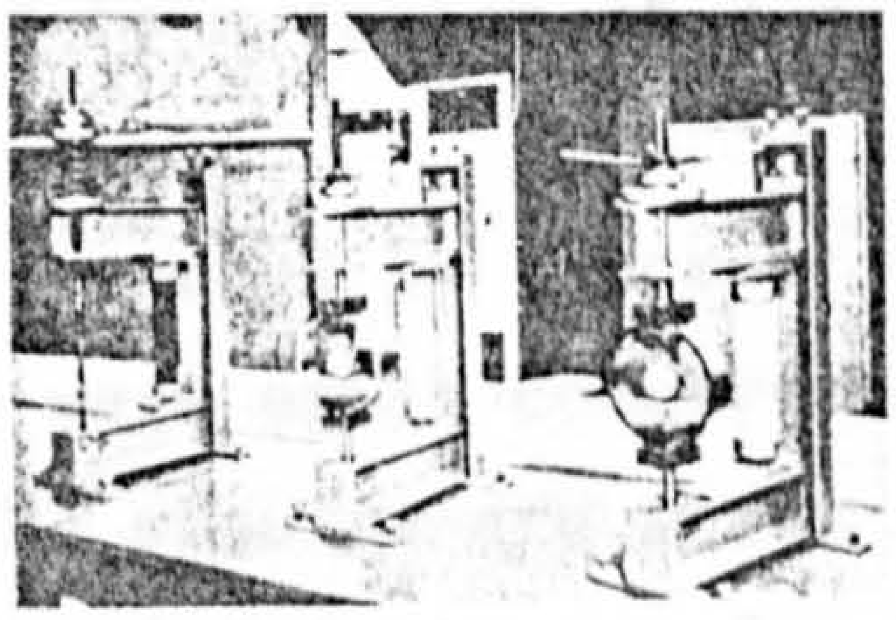


Figure 49.1 : Creep Machines (Neville's is shown on the left; Lenczner's is illustrated in the center and on the right.)

Taken from: David Lenczner, "The Design of Creep Machines for Brickwork," Proceedings of the British Ceramic Society, n.4, July 1965, p. 7.

levels between 334 and 674lbf/in^2 (2.3 to 4.6 N/mm^2). The strain for each mix was obtained by algebraically deducting the strain of the control specimen due to temperature and moisture changes from the total strain suffered by specimens under load. The compressive strength and creep results are reproduced in Tables 14 & 15.

The results of these tests showed that both elastic (or immediate strain) and creep were higher with the weaker 1:1:6 mix, but elastic recovery was smaller than that for the 1:½:3 mix. Lenczner attributed this smaller recovery for the 1:1:6 mix to its more viscous nature.[36] In comparing the actual values of maximum creep strains at similar stress levels for the two mixes, Lenczner also noted that the 1:1:6 mix's values increased by a factor of 2.5 to 3.5 times the values obtained with the 1:½:3 mix.[37]

Additional tests were reported by Lenczner in 1976, with consistent results.[38] Brickwork piers were again constructed using two mortar mixes: 1:½:3 and 1:1:6. The results are shown in Graph 4. Again the maximum creep strains for the 1:1:6 mix are 2 - 3 times larger than those strains for the 1:½:3 mortar. The compressive strength of the 1:½:3 mortar was 16.1 N/mm^2 and that of 1:1:6 mix was 7.8 N/mm^2.[39]

From the results of this test program, Lenczner suggested that creep in brickwork ceases after a shorter time than in concrete where it can go on for many months and possibly years.[40]

In 1977 Neville published further creep results, mostly concerning concrete, and including comparisons of creep in compression and tension.[41] His results for creep in compression are consistent with those obtained by Lenczner. He confirmed that basic creep in compression decreases with time and is 40% (or more) recoverable.[42] He also found that age at loading reduces basic creep in compression (Graphs 5 & 6).

Neville indicated a direct proportionality between creep and the applied stress, but only where the stress does not exceed one-half of the ultimate strength. Under higher stresses, a direct proportionality no longer existed.[43] Furthermore, he found creep to be inversely

Mean Compressive Strength in N/mm^2 for 3" mortar cubes

Mortar			
1:¼:3		1:1:6	
7 days	28 days	7 days	28 days
12.67	16.07	4.32	7.79

TABLE 14—CREEP RESULTS FOR BRICKWORK WITH 1:¼:3 MORTAR

Applied stress (lb/in²)	E (lb/in² × 10⁶)	Instant. strain (× 10⁻⁵)	Max. load strain (× 10⁻⁵)	Max. creep strain due to load (× 10⁻⁵)	Max. load strain / Instant. strain	Elastic recovery on removal of load (%)
247	4·05	6·1	7·8 after 5 weeks	1·7	1·28	100
406	3·50	11·6	13·9 after 4 weeks	2·3	1·20	87
630	3·56	17·7	21·6 after 12 weeks	3·9	1·22	79
870	3·54	24·6	31·9 increasing	7·3 increasing	1·29	80

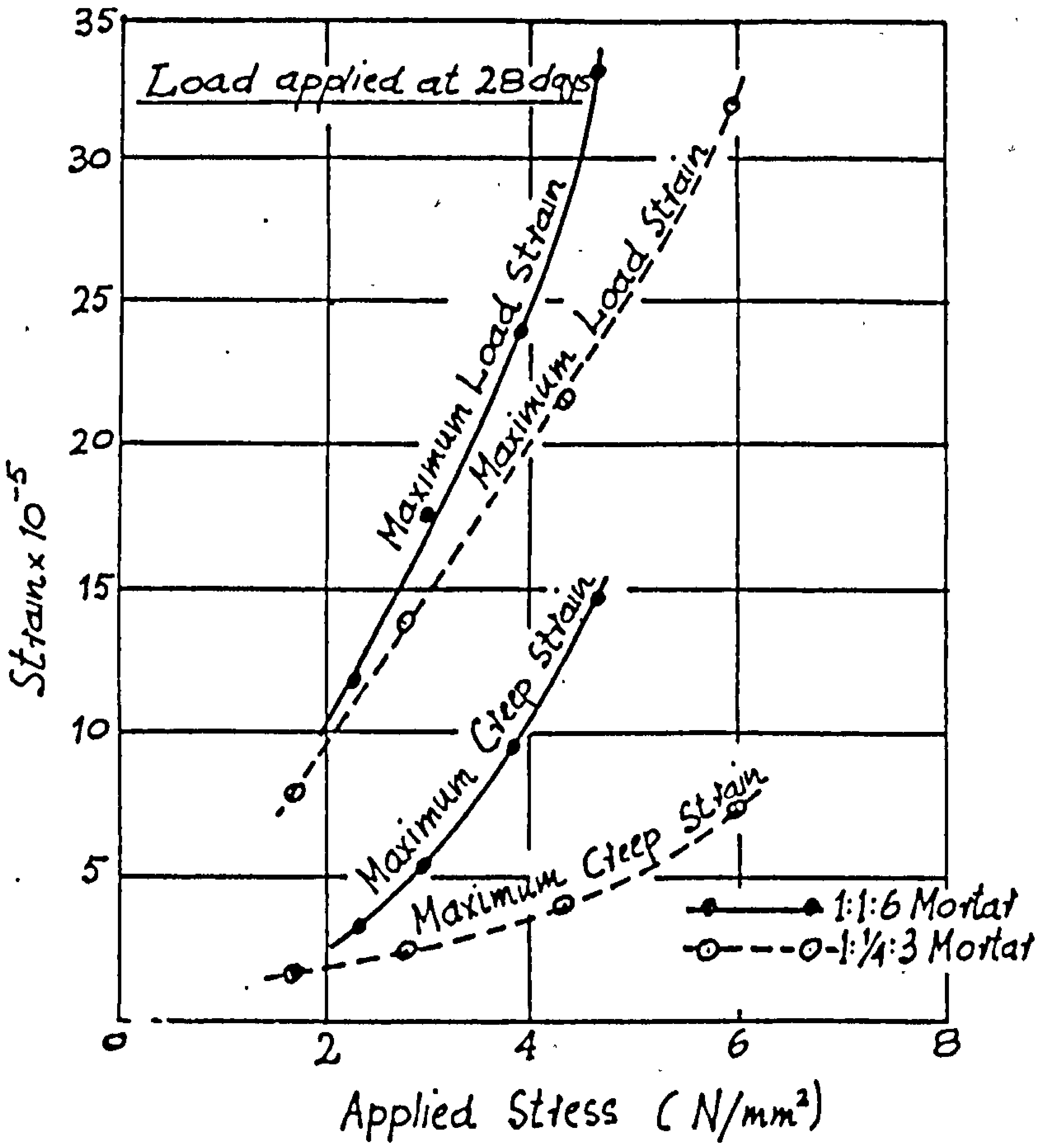
TABLE 15—CREEP RESULTS FOR BRICKWORK WITH 1:1:6 MORTAR

Applied stress (lb/in²)	E (lb/in² × 10⁶)	Instant. strain (× 10⁻⁵)	Max. load strain (× 10⁻⁵)	Max. total strain (× 10⁻⁵)	Max. creep strain (× 10⁻⁵)	Max. total less instant. strain (× 10⁻⁵)	Max. load strain / Instant. strain	Elastic recovery on removal of load (%)
334	3·96	8·5	11·9 after 13 weeks	4·9	3·4	—3·6	1·40	74
422	3·50	12·1	17·5 after 15 weeks	10·3	5·4	—1·8	1·45	73
560	3·76	14·9	24·6 after 16 weeks	17·5	9·7	2·6	1·65	44
674	3·66	18·4	33·1 after 13 weeks	31·2*	14·7	—	1·80	31

*This reading includes temperature strain in the bracket supporting the displacement transducer.

Tables 14 & 15: Creep (and Strength) Results for Brickwork with 1:¼:3 and 1:1:6 Mortars.

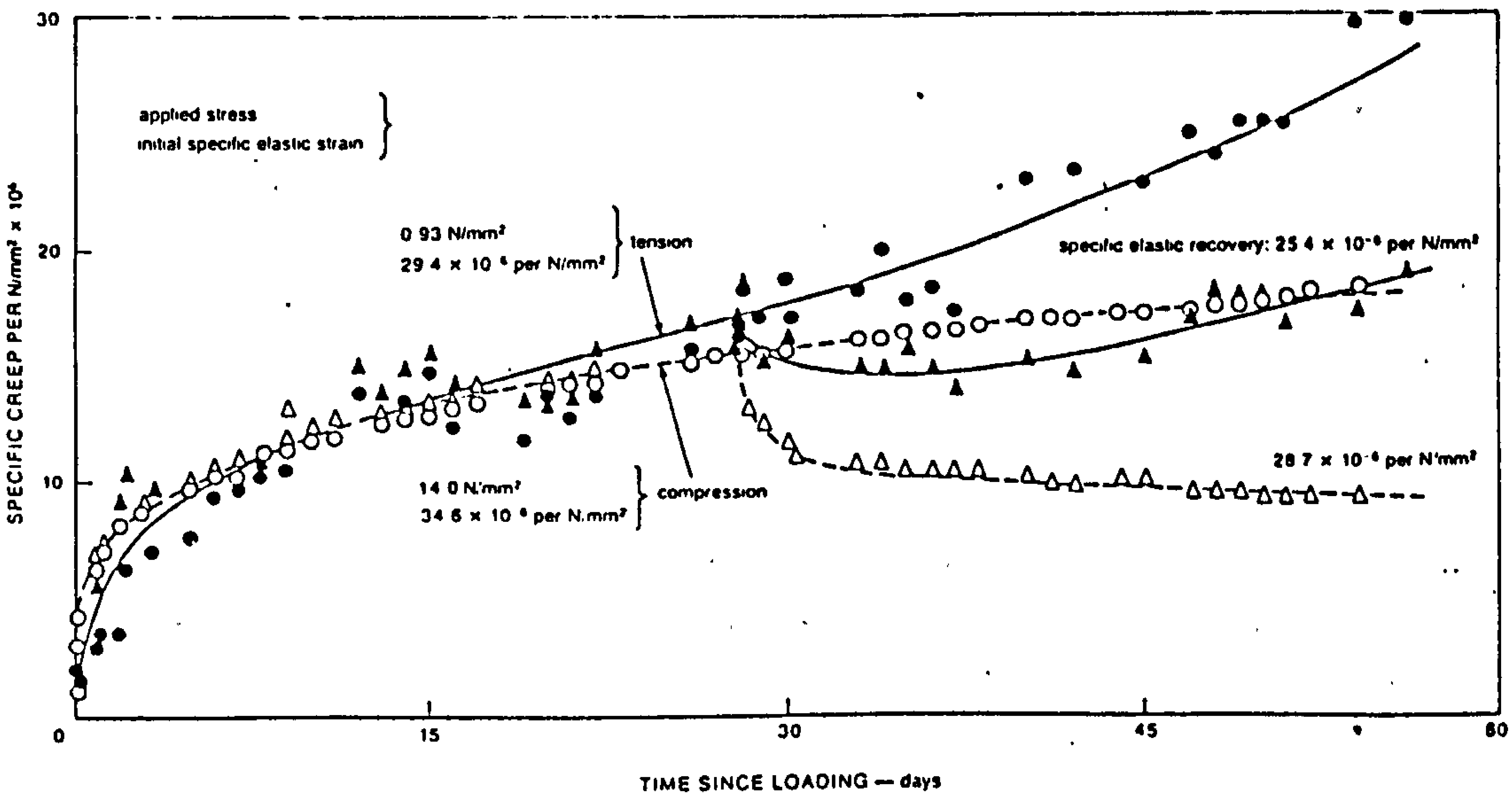
Taken from: D. Lenczner, "Creep in Brickwork," <u>Proceedings of the 2nd International Conference on Brick Masonry</u>, SIBMAC, Apr. 1970, pp. 46 - 48.



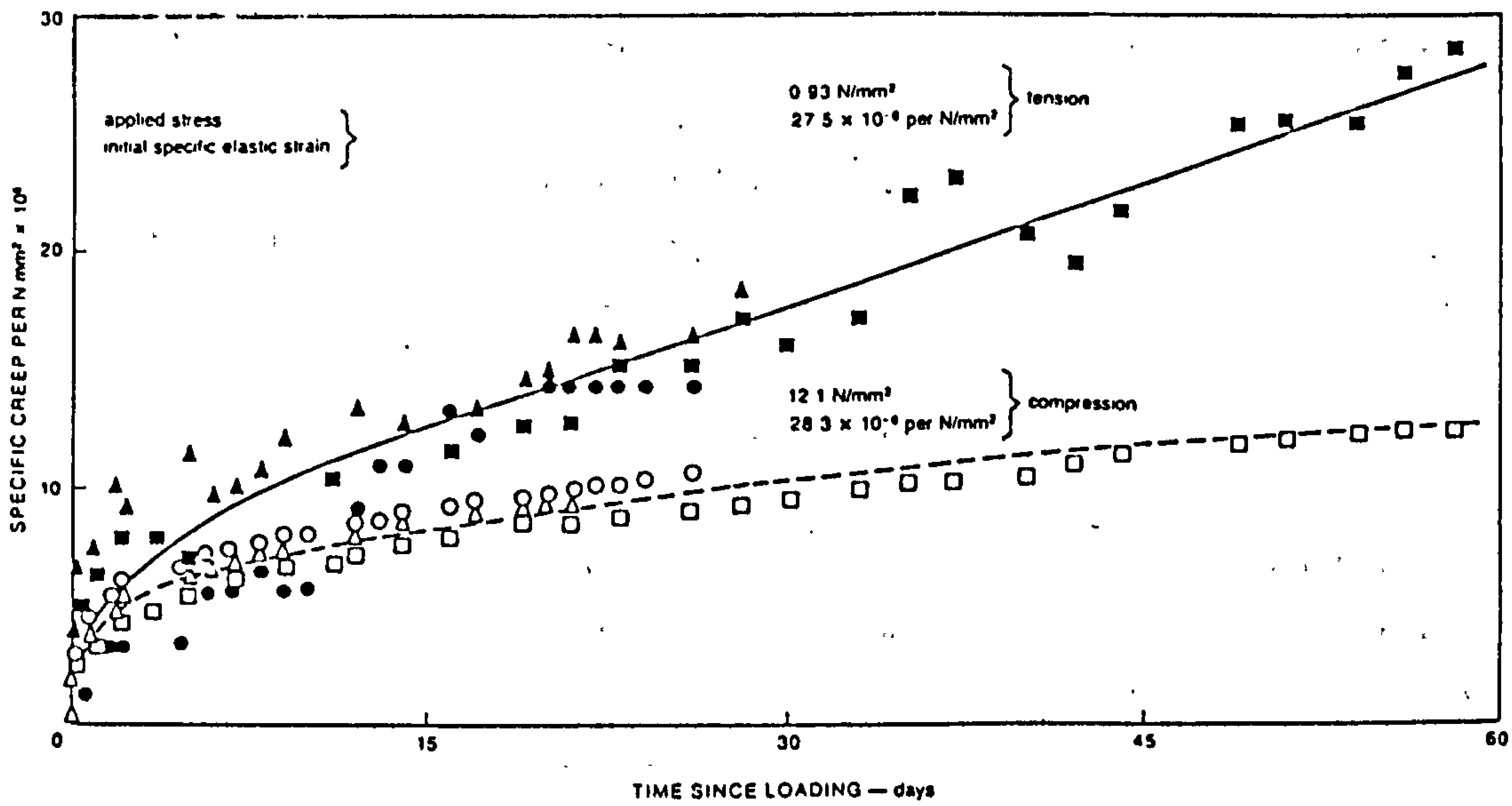
Graphs of maximum load and creep strains plotted against applied stress for the Butterly engineering brick and two types of mortar.

Graph 4: Data Results Graphically Showing How Creep is Influenced by the Mortar Mix Used.

Taken from: D. Lenczner, "Creep and Moisture Movements in Brickwork and Blockwork," Proceedings of the Conference on Performance on Building Structures, 1976, p. 372.



Basic creep and creep recovery in tension and in compression for concrete stored in water, loaded at the age of 28 days and unloaded at the age of 56 days.



Basic creep in tension and in compression for concrete stored in water, loaded at the age of 56 days.

Graphs 5 & 6: Graphs Showing How Age Influences Creep.

Taken from: J.J. Brooks and A.M. Neville, "A comparison of creep, elasticity and strength of concrete in tension and in compression," Magazine of Concrete Research, v. 29, n. 100, Sept. 1977, pp. 137 - 38.

proportional to the strength of concrete at the time of loading.

Neville also touched on the relationship between creep and shrinkage; no specifics were given, just generalizations.[44] He stated that concrete which exhibits high shrinkage generally also shows a high creep.

In summary, while both Lenczner and Neville have conducted extensive experiments which indicate that creep and mortar constituents are related, and which lay sufficient background for design of future tests programs, they made no tests on mortar alone, varying the mixes. Furthermore, their published results all state that controls were maintained, and moisture and temperature recorded, but none of the shrinkage data was ever published. Consequently, these are two areas requiring more intensive research.

Conclusions

Once data have been obtained from testing, correlations and other relationships need to be established and analyzed. These are best presented in the forms of tables and graphs. If uniformity is maintained in the laboratory procedures, then comparisons can also be made between research conducted by different individuals. Such was the case with creep of concrete and masonry.

As previously stated, a large part of the total creep strain in a wall occurs in the mortar bed joints. Creep in mortars may be beneficial in relieving concentrations of stress. Lenczner and Neville have shown that the potential to creep is influenced by the properties and mix proportions of mortar, creep being greater in mixes rich in lime.[45] Thus, potential to creep should be one criterion in selecting a mortar.

The creep and shrinkage research reported in the next chapter was conducted in a laboratory similar in conditions to those reported above, and was undertaken to obtain further data on creep, especially of lime-rich mixes.

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3. BRE, Digest 160, 1.

4. In Britain, an expansion joint of 10mm is recommended per approximately every 12m. BSI, CP121, 17.

5. Ramsey, Standards, 313.

6. Lenczner, "Creep and Moisture Movements," 370.

7. David Lenczner, Movements in Buildings (Oxford, England: Pergamon Press, 1981), p. 35.

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13. The Limestone Federation, Lime in Building (London: The Limestone Federation, 1980?).

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27. Lenczner, "Creep and Moisture Movements," 373.

28. See the Bibliography for a complete listing of consulted works by Lenczner and Neville.

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30. J.J. Brooks and A.M. Neville, "A comparison of creep, elasticity and strength of concrete in tension and in compression," Magazine of Concrete Research, v. 29, n. 100, Sept. 1977, p. 133.

31. Lenczner, "Creep in Brickwork," 45; Lenczner, "Creep and Moisture Movements," 373; and David Lenczner, interview of November 1982, Cardiff, Wales.

32. David Lenczner, "The Design of Creep Machines for Brickwork," Proceedings of the British Ceramic Society, n. 4, July 1965, p. 7; and A.M. Neville, "The measurement of creep of mortar under fully controlled conditions," Magazine of Concrete Research, v. 9, n. 25, March 1957, p. 10.

33. A.D. Ross, "The creep of Portland blast-furnace cement concrete," Journal of the Institution of Civil Engineers, v. 8, n. 4, February 1938, pp. 43-52.

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36. Lenczner, "Creep in Brickwork," 48.

37. Lenczner, "Creep in Brickwork," 46.

38. Lenczner, "Creep and Moisture Movements."

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Chapter 6: Creep and Shrinkage Testing

Introduction

A test program was planned to investigate the creep and shrinkage of mortars of varying composition. Whereas others have tested concrete and brickwork piers, no such study has been made to compare samples of mortar mixes alone. A wide range of mortar mixes was therefore tested, measuring shrinkage, crushing strength, elastic strain and recovery, weight loss, and creep. The aim was to add to existing knowledge ot mortar and to present the data in a form which can be applied to actual situations encountered in the field, particularly in choosing the most suitable mortar for a particular restoration or repair project.

Creep in mortar was the property chosen for study because it represents deformation without cracking; Lenczner found 60 - 80% of deformation of a wall occurred in the mortar bed joints. Although creep is not the sole form of strain, it is a component worthy of intensive study. A range of mixes were tested to enable a full picture of mortar to be developed, however some individual mixes were selected due to their popular use by organizations such the Department of the Environment (D.O.E.) in Great Britain or their frequent mention in such documents as building codes.

A controlled laboratory environment and constant test methods were maintained to insure that the test data were comparable.

Laboratory Environment

To ensure that results were not unintentionally affected by external factors, and to achieve compatibility with the creep tests conducted by Lenczner and Neville, the laboratory, situated in the basement of the Department of Architecture, University of Edinburgh, was air conditioned. The room was locked and access limited. This allowed the environment to be strictly controlled.

Climate-control equipment was installed several months before the actual testing began, to allow for adjustment.[1] A thermo-hygrograph was included to record the temperature and humidity continuously for the duration of the experiments. By mid-October 1982 satisfactory mean temperature and relative humidity readings were achieved. The mean average temperature was 19.69°C (68°F) with a standard deviation of 0.4°C (0.7°F). The mean average humidity was 56.96% with a standard deviation of 1.8%. Table 16 gives a record of the weekly temperature and humidity readings.

Design and Construction of Testing Equipment

The key piece of equipment used in this program was the creep machine. The loading principle differed from Lenczner or Neville's nutcracker principle, as discussed in Chapter 5. A lever was employed (Figures 50 & 51). Weights were placed on the rack hanging from one end of the lever. This pressed mortar cylinders, previously plastered into place on the loading platen of the machine, into compression with a force 11 times the load applied to the lever.

The creep machines were designed by E.C. Ruddock and built by the Architecture Department's workshop staff from components of the Wykeham Farrance Engineering Ltd.'s soil consolidation machine.[2] The four individual machines were bolted to a steel table which, in turn, was bolted to the concrete floor. This was done to minimize movement or stress caused by bumping the table or vibrations in the building. The area was roped off to prevent close access as the laboratory was also used to make and prepare the mortar cylinders.

The cube and cylinder moulds were the two other pieces of testing equipment employed. Again following precedents set by Lenczner and Neville, a 2" diameter x 9-3/4" long (or 5 cm x 24-1/3 cm) cylindrical form was selected as the shape of the specimen for creep and shrinkage testing. Ten centimeter (4") mortar cubes were chosen for testing the

Week of:	Temperature in ^{o}C			Humidity in %		
	High	Low	Mean	High	Low	Mean
Oct.11 '82	22.50	20.00	21.25	58.0	56.0	57.00
18	20.50	19.50	20.00	57.0	56.0	56.50
25	20.00	19.50	19.75	58.5	56.0	57.25
Nov. 1	20.00	19.50	19.75	58.5	56.0	57.25
8	20.50	19.75	20.12	57.0	56.0	56.50
15	20.75	19.50	20.12	58.0	55.0	56.50
22	20.75	20.25	20.50	58.5	55.0	56.75
29	20.50	20.00	20.25	57.5	54.0	55.75
Dec. 6	20.00	20.00	20.00	57.0	55.0	56.00
13	19.75	19.50	19.62	57.5	54.0	55.75
20	19.50	19.50	19.50	56.0	54.0	55.00
27	19.00	19.00	19.00	56.0	56.0	56.00
Jan. 3 '83	19.50	19.00	19.25	59.0	56.0	57.50
10	19.75	19.00	19.37	60.0	57.0	58.50
17	19.50	19.50	19.50	59.0	56.0	57.50
24	19.75	19.50	19.62	59.0	56.5	57.75
31	19.75	19.50	19.62	57.0	53.0	55.00
Feb. 7	20.00	19.50	19.75	58.0	51.0	54.50
14	20.00	19.75	19.87	58.5	54.0	56.25
21	19.75	19.50	19.62	56.5	50.0	53.25
28	20.00	19.50	19.75	56.5	53.0	54.75
Mar. 7	20.00	19.75	19.87	56.0	53.0	54.50
14	19.75	19.50	19.62	56.5	55.0	55.75
21	20.00	19.75	19.87	56.0	55.0	55.50
28	19.50	19.50	19.50	56.0	56.0	56.00
Apr. 4	19.50	19.50	19.50	57.5	57.5	57.50
11	19.50	19.00	19.25	63.0	53.0	58.00
18	19.50	19.25	19.37	59.0	53.0	56.00
25	19.50	19.50	19.50	62.0	56.0	59.00
May 4	20.00	19.75	19.87	59.0	54.0	56.50
16	20.00	19.50	19.75	59.0	56.0	57.50
23	20.00	19.50	19.75	62.0	55.0	58.50
30	19.75	19.50	19.62	62.0	57.0	59.50
June 6	19.50	19.50	19.50	64.0	57.0	60.50
13	19.50	19.00	19.25	64.0	56.0	60.00
20	19.50	19.00	19.25	64.0	59.0	60.00
27	19.00	19.00	19.00	64.0	59.5	61.75
Mean average:			19.69			56.96
Standard deviation:			0.4098			1.81

Table 16: Temperature and Humidity Control

The above data shows that the temperature and humidity control with error was: 19.96^{o} with a deviation of 0.4098 and 56.98% with a deviation of 1.81. Note that during the weeks of January 3; March 28; and April 4 the temperature and humidity were stable. These were holiday periods when the heat was turned off in the building. Also, fewer people were in the laboratory and then only for a few minutes each day.

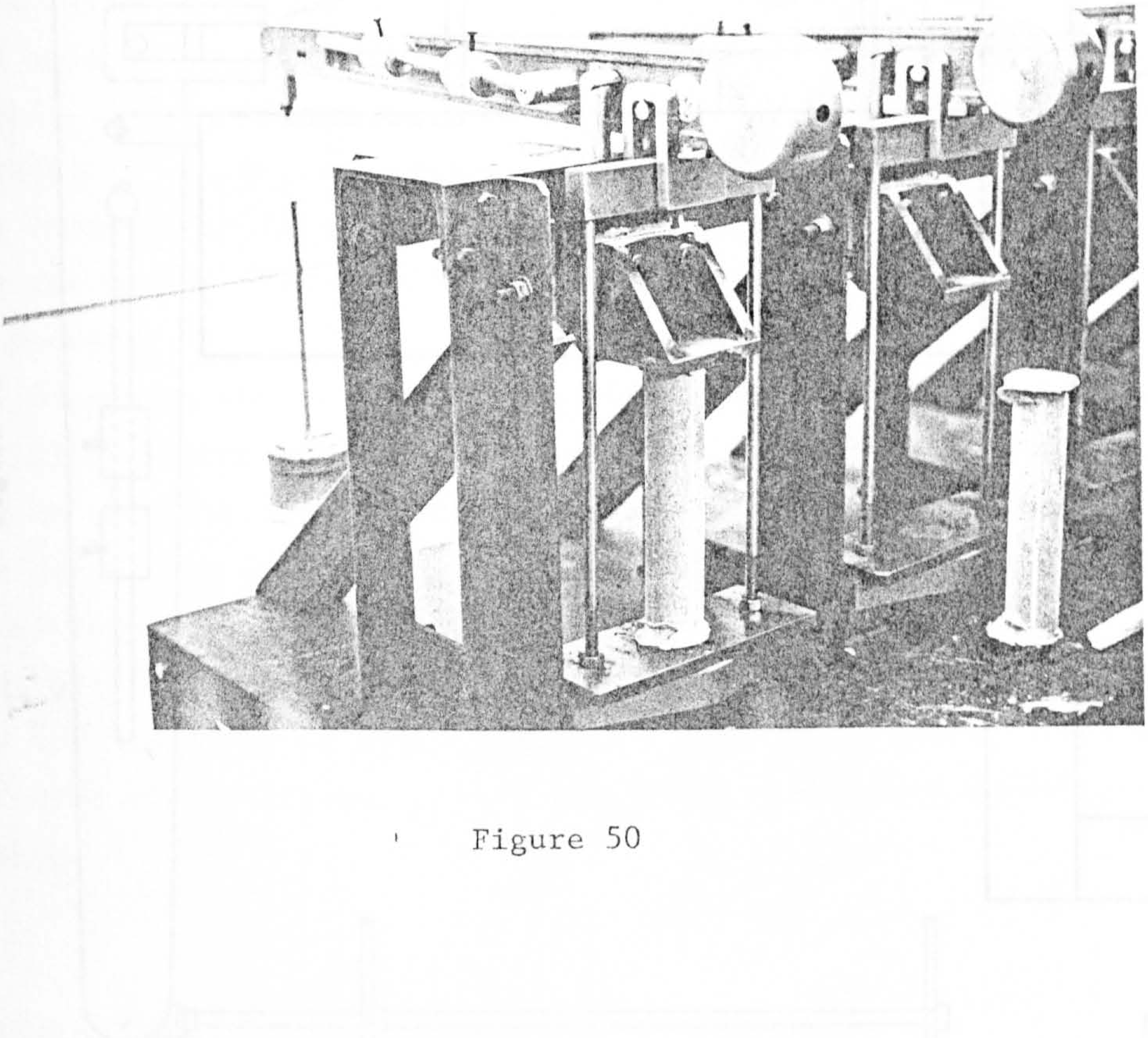
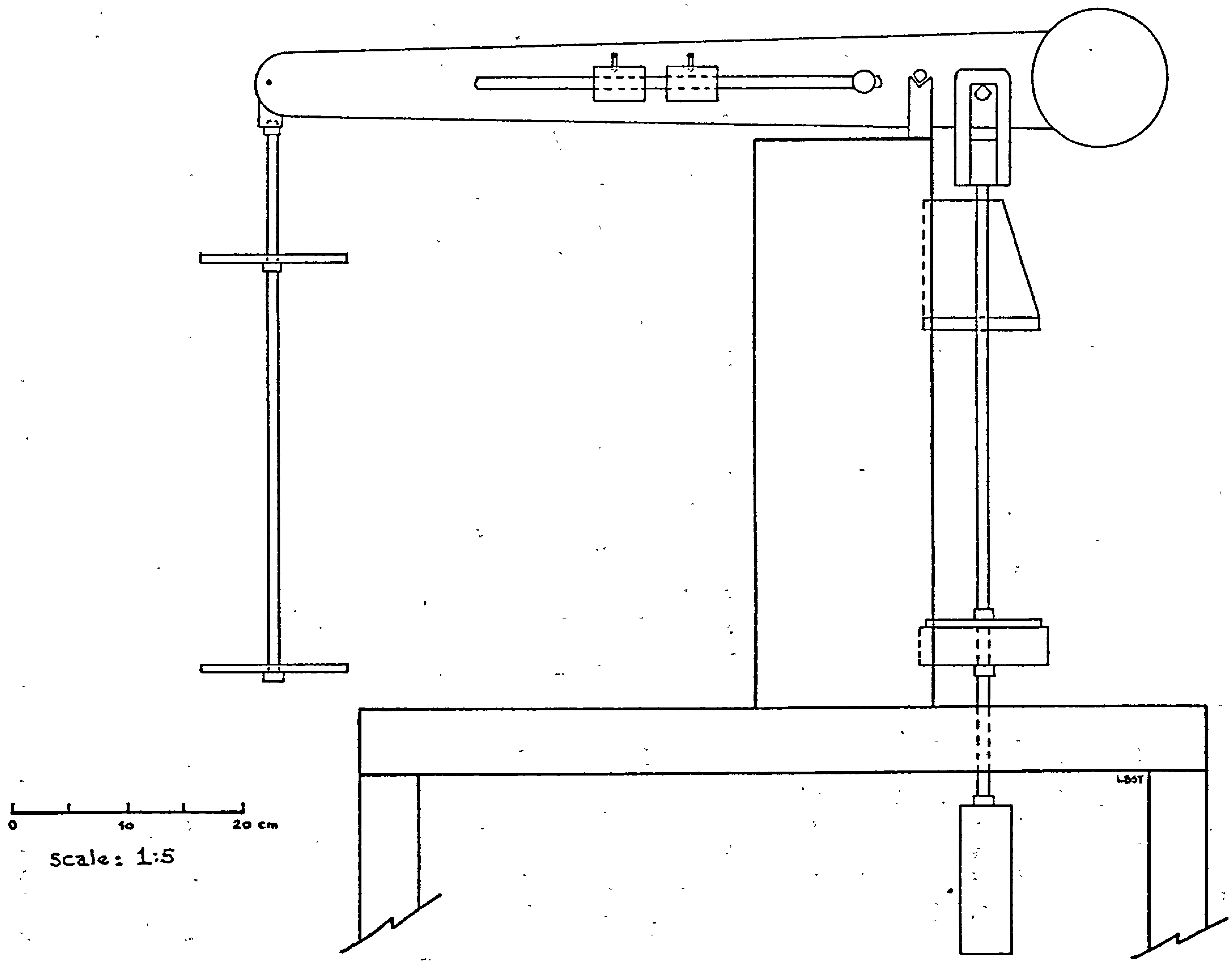


Figure 50

Figure 51



Scale: 1:5

crushing strength of the various mixes.[3]

The cubes were made from steel moulds consisting of five pieces: four sides and a bottom. Initially all parts were brushed with an oil to act as a mould release. Then, when the sides were bolted together and the bottom attached by springs to two opposite sides, the mould was ready to receive the mortar (Figure 52).

To produce the cylinders, however, steel moulds were ruled out due to the potential difficulty in removing a cylindrical sample of low strength in one piece.[4] One of the main problems was that the weaker mixes often cracked or broke during removal. Different attempts were made to determine the best way to release the mortar from a mould. Finally, a high density plastic pipe with a 5 cm (2") inner diameter was purchased.[5] It was cut into 25-2/3 cm (10½") lengths and a steel base inserted at one end (Figure 53). The mould was oiled, and filled with the mortar (Figure 54). The mortar was tamped down to eliminate air pockets.

To remove the cylinder after the mortar had set, the base was carefully twisted off and four even, shallow cuts made in the plastic with an electric saw (Figure 55). A fifth cut was made about 1½ cm (½") from one of the others. Each cut was deepened with a razor blade; this procedure prevented the cylinder itself from being marked. With the use of pliers, the plastic strip produced from the two close cuts was pulled away and the cylinder then eased free (Figures 56 & 57). This method destroyed the mould, but proved effective in avoiding cracks and breakage.

Material Storage

All materials were purchased in single batches from local suppliers so that there were sufficient quantities to last throughout the testing period.[6] This ensured that each bag of each material came from the same manufacturing batch.

The Portland cement, hydrated lime, and hydraulic lime were emptied

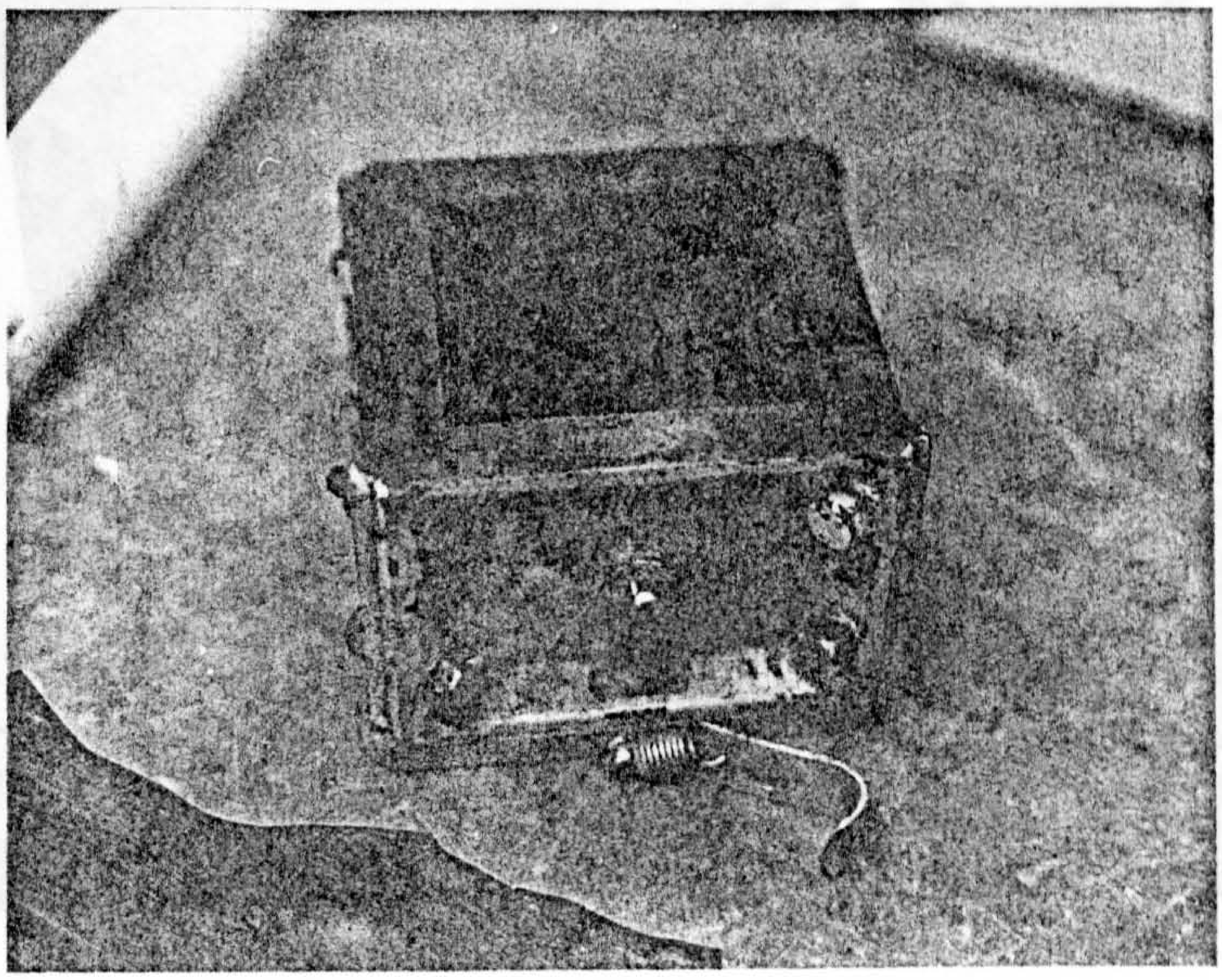


Figure 52

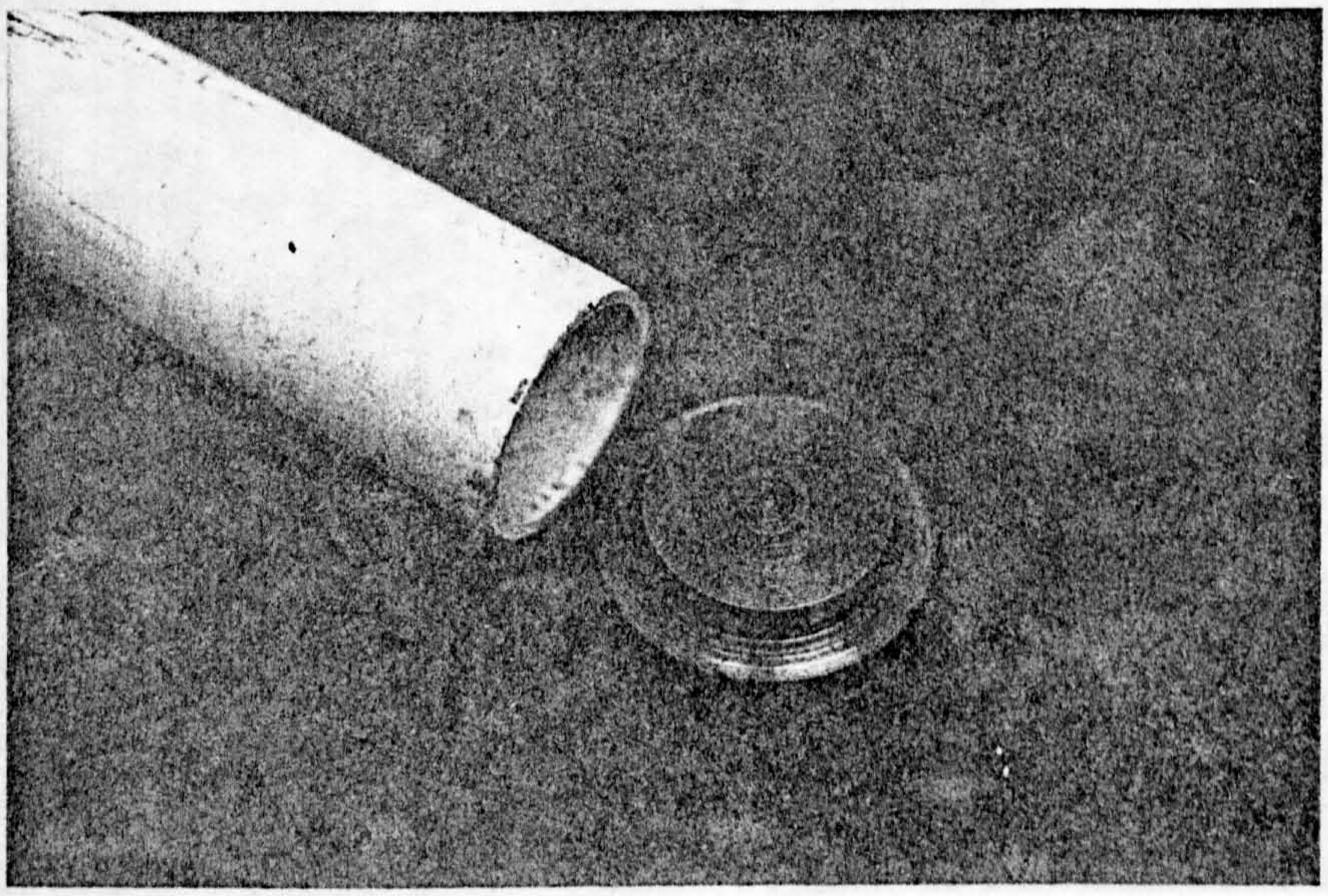


Figure 53

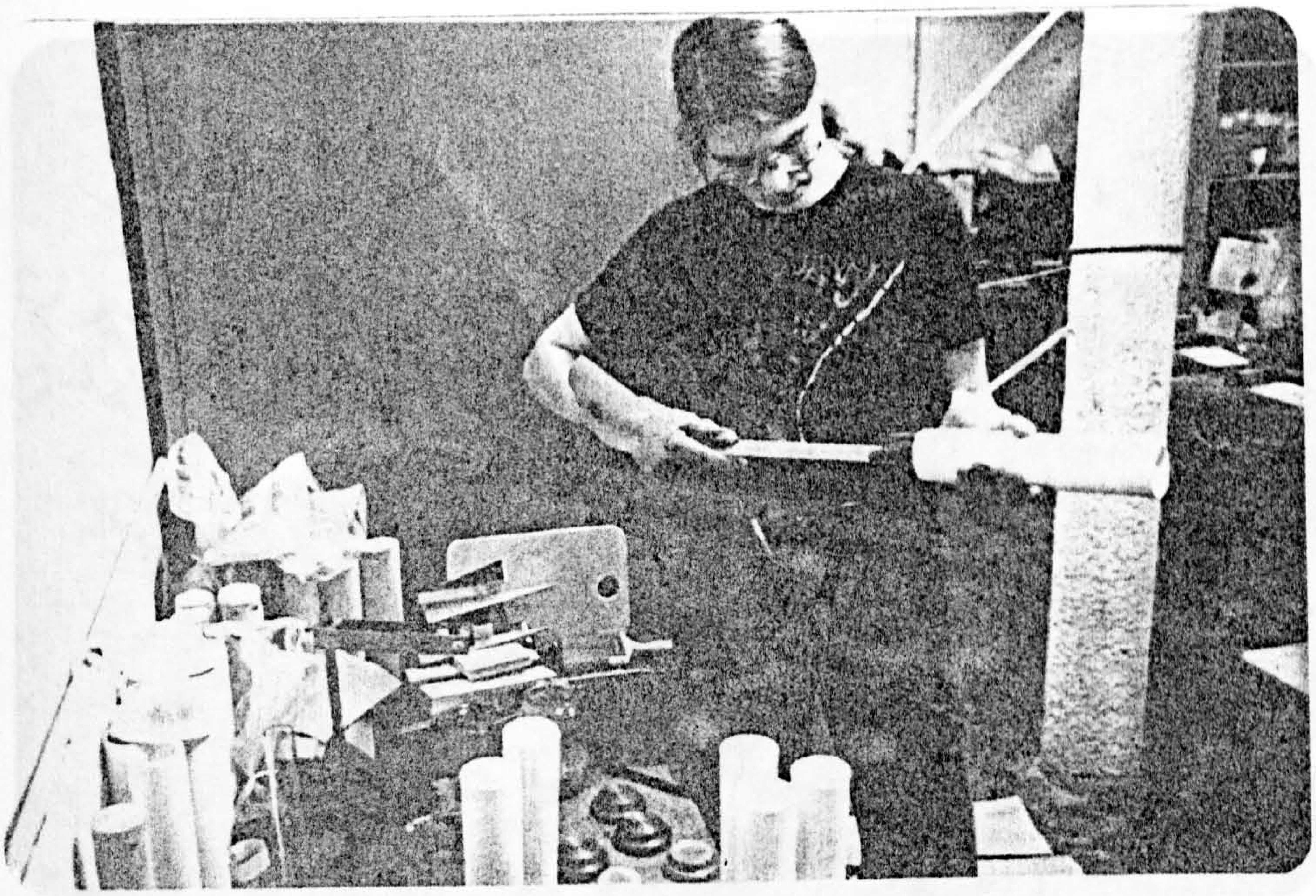


Figure 54

Figure 55

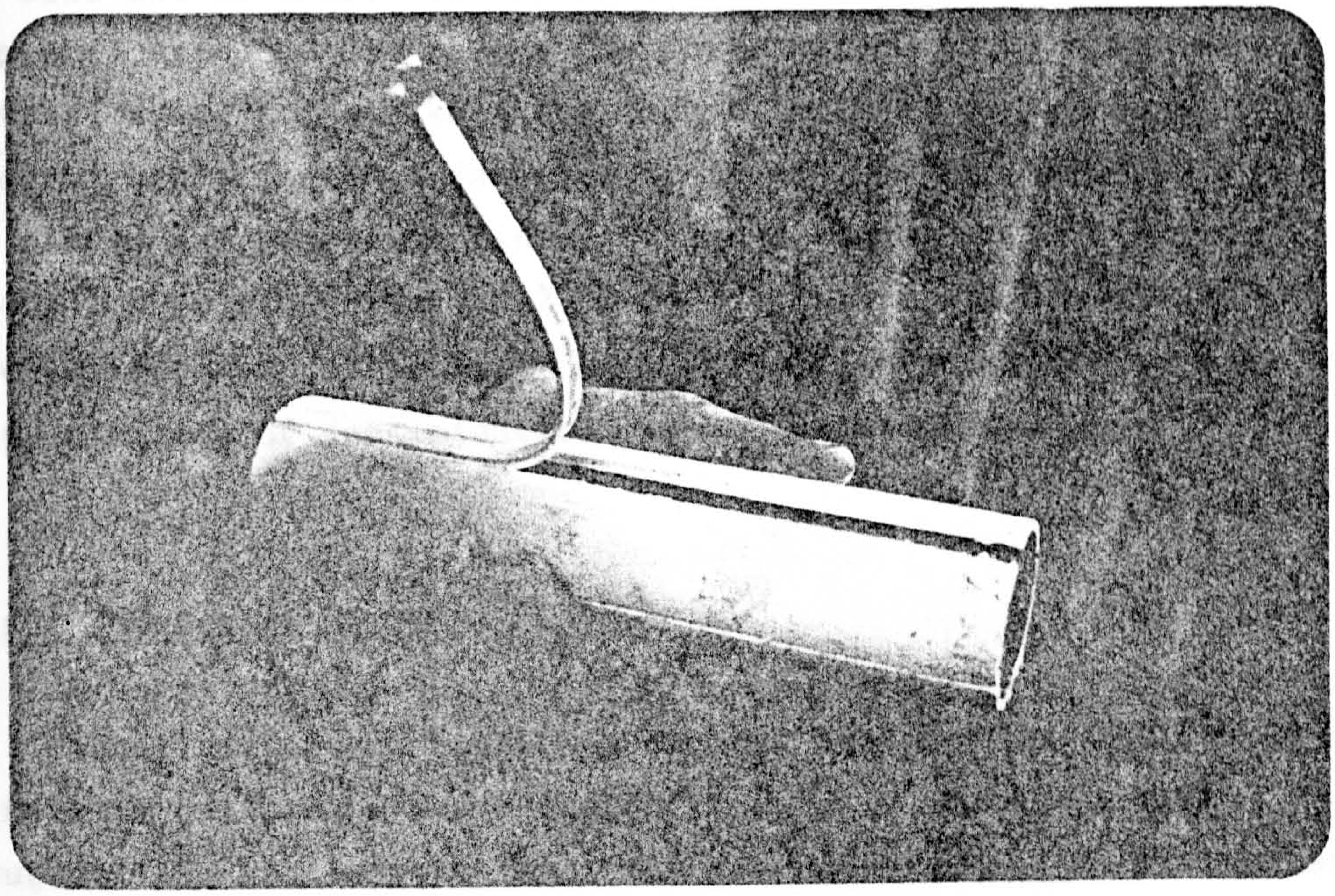


Figure 56

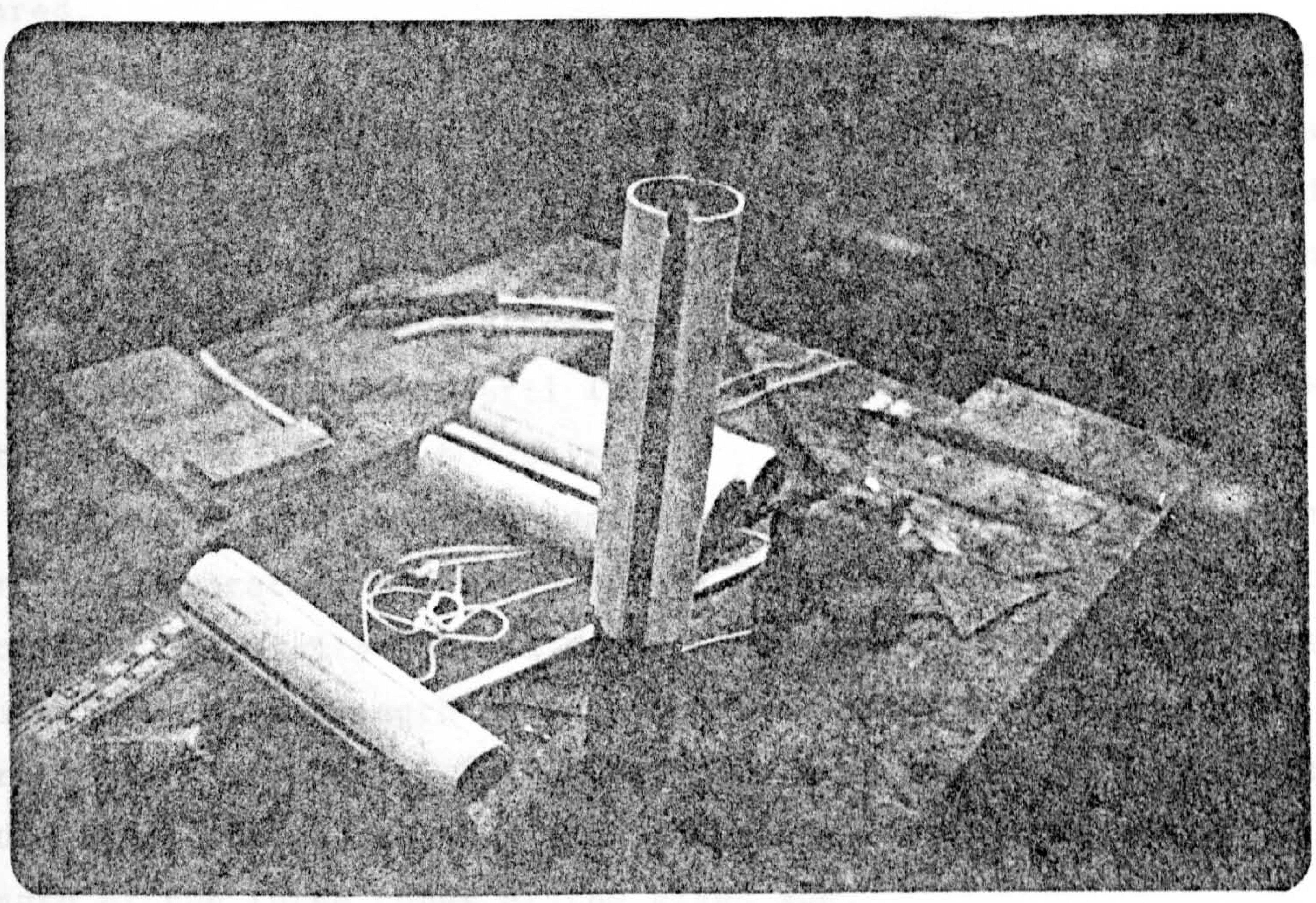


Figure 57

into bins and covered. In the case of the cement, plastic cling-film was placed over the bin before the cover to prevent air and dust penetration and to help keep the cement fresh (Figure 58). The builders' sand came in a dampened state and was air dried on a table, then sifted and stored in bins. As large pieces of gravel were found in the sand, a British Standard 2.36 mm mesh sieve was used to filter out and discard these particles. Each bin had its own scoop to eliminate the possibility of contamination from a shared scoop.

Control Testing of Materials

Control tests were conducted on both the sand and the cement to ensure that uniformity was being maintained in these materials throughout the testing program. For the cement, this meant evaluating its strength in a standard mortar and, for the sand, determining, through grading tests, if grain sizes were evenly dispersed in each mix made. The sand and cement data obtained from the first mortar mix served as the specification or guide to which subsequent results were compared.

When the bag of Portland cement was opened and poured into its bin in early October 1982, a portion was used immediately to make mortar mix #1: a 1:0:3--1 part Portland cement, 0 part lime, and 3 parts sand. Six cubes and ten cylinders were made from this mix. To ensure constant strength over the nine-month test period, six more sample cubes of the same mix were made in mid-April 1983. As before, they were aged two lengths of time: 28 and 60+ days.[7]

At the end of each aging period, three cubes were removed from the controlled laboratory and taken to the Building Department laboratory of Heriot-Watt University where a compression testing machine was located (Figure 59). The strength of each cube was determined by crushing it to destruction (Figure 60). Each cube broke into the shape of an hourglass (Figure 61).[8] An average was then calculated for the crushing strength of the three cubes at the given age.

Table 17 gives specific information on the 12 cubes made, and Graph

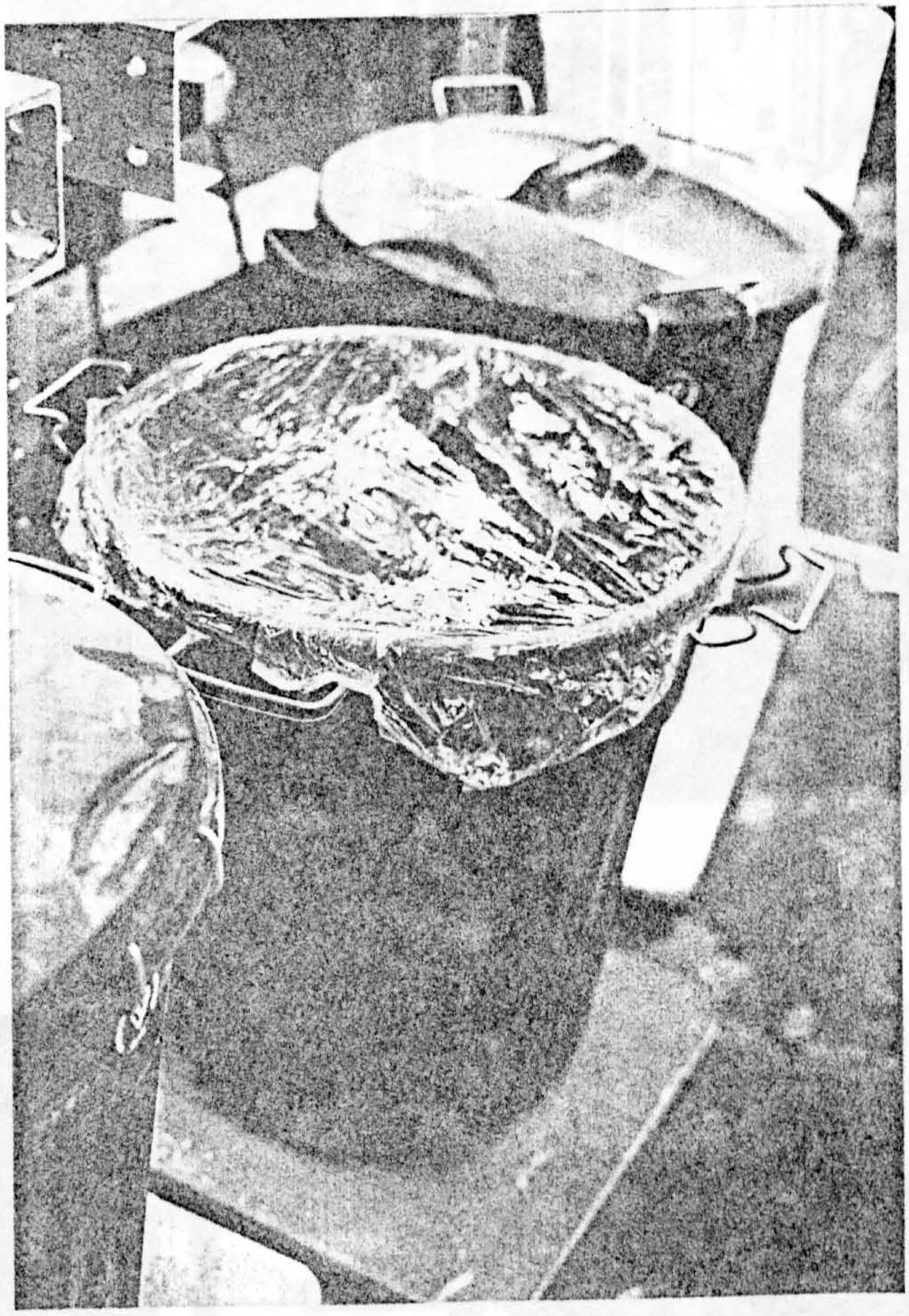


Figure 58

Figure 59

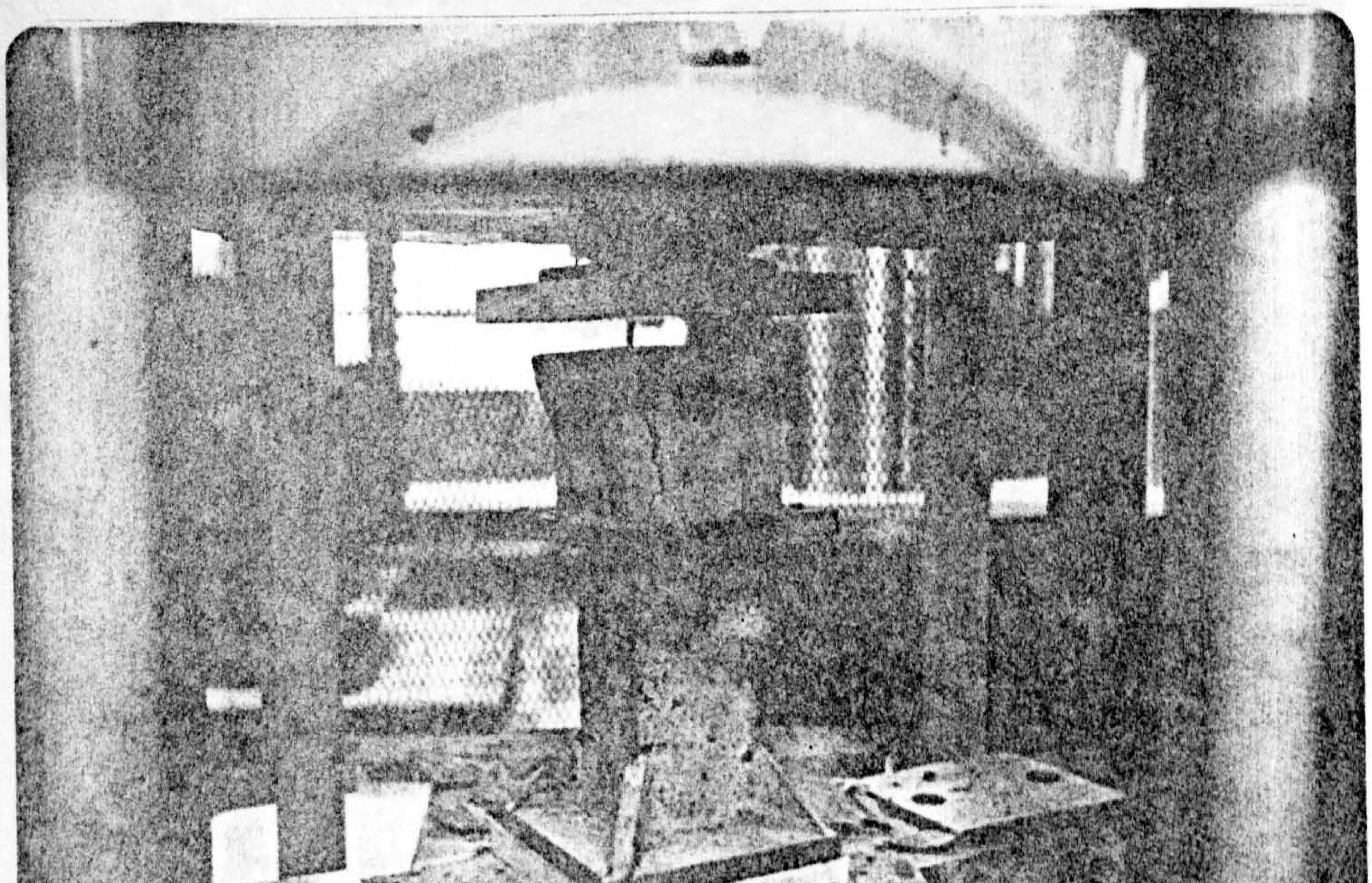


Figure 60

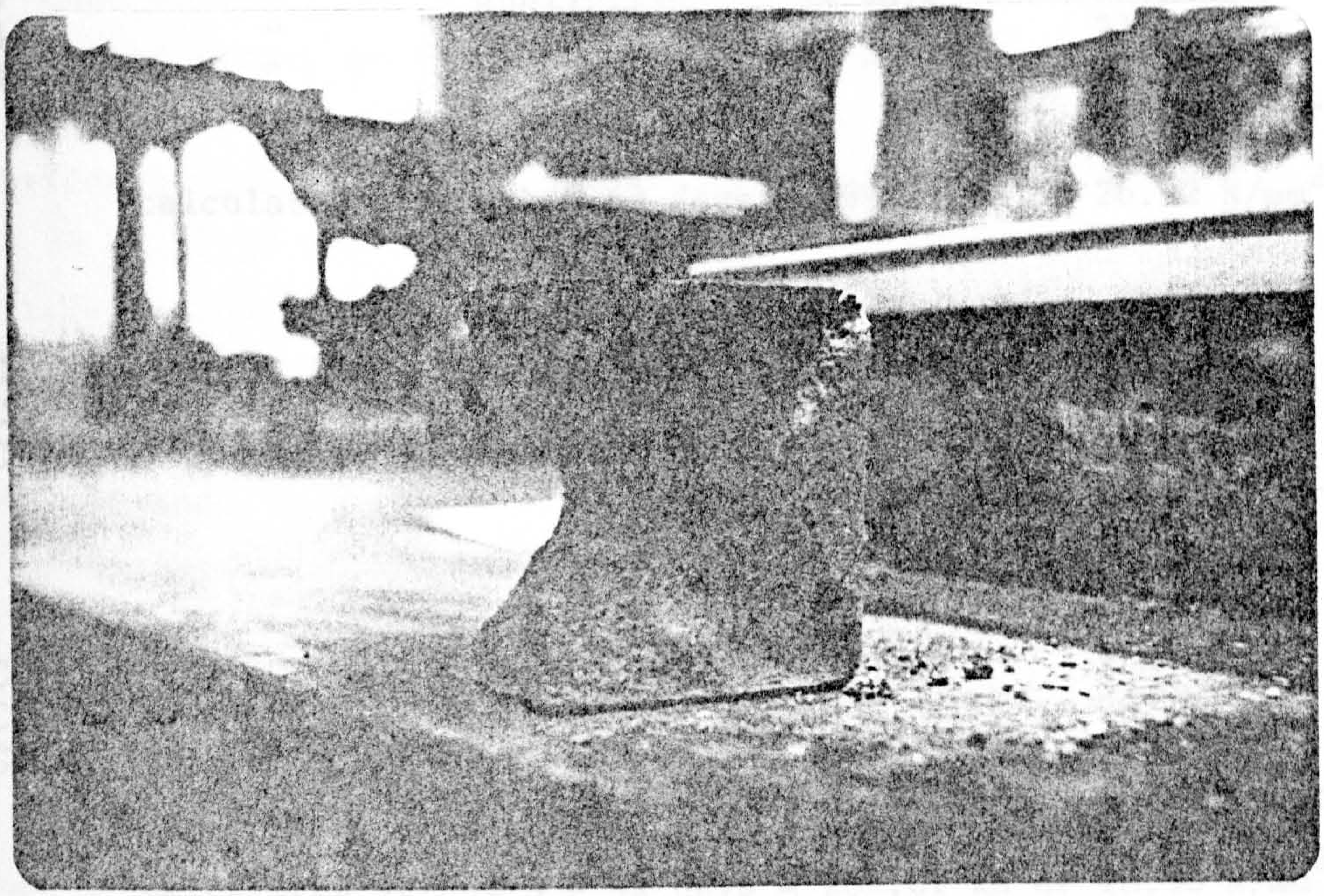


Figure 61

Cube #	Date Made	Crush. Date	Age	Crush. Strength	
1-B	Oct.11,1982	Nov. 8,1982	28 days	245.50 kN	
2-B	"	"	"	257.00	
3-B	"	"	"	252.00	
			AVERAGE:	251.50	or 25.15 N/mm^2
4-B	"	Jan.10,1983	91 days	282.00 kN	
5-B	"	"	"	278.00	
6-B	"	"	"	290.00	
			AVERAGE:	283.34	or 28.33 N/mm^2

*calculated strength @ 63 days = 269.19 kN or 26.92 N/mm^2

Cube #	Date Made	Crush. Date	Age	Crush. Strength	
1-C	Apr.11,1983	May 9,1983	28 days	235.00 kN	
2-C	"	"	"	237.00	
3-C	"	"	"	251.00	
			AVERAGE:	241.00	or 24.10 N/mm^2
4-C	"	June13,1983	63 days	248.00 kN	
5-C	"	"	"	282.00	
6-C	"	"	"	273.00	
			AVERAGE:	267.67	or 26.77 N/mm^2

*calculated strength @ 91 days = 289.01 kN or 28.90 N/mm^2

Table 17: Cement Grading Test Data
This data was compiled over the nine-month testing period to determine if the cement's strength had altered considerably from October 1982 to June 1983.

*To allow comparisons to be made and to ensure uniformity, estimated strengths were calculated by linear interpolation: 63-day strength for the 91-day old cubes, and 91-day strength for the 63-day old cubes.

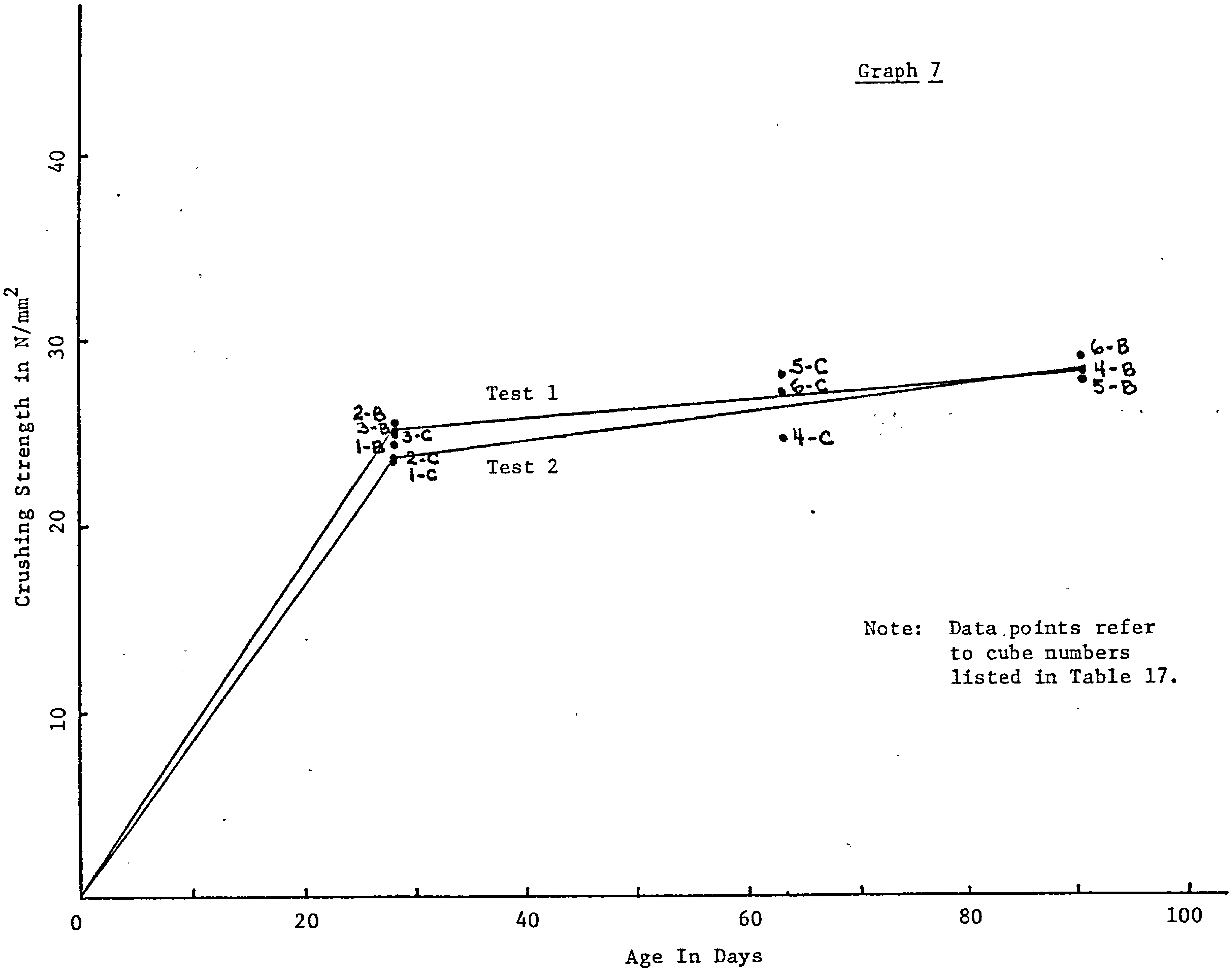
7 displays the individual crushing data for each cube. The results of this cement test clearly show that while the strength of the six cubes made April 11, 1983 had diminished slightly at 28 days of age, it was not considerable.

The builders' sand employed in the tests, as previously mentioned, consisted only of those grains passing through a 2.36 mm sieve. This sieving process served two functions: to eliminate large pebbles and to aid in evenly dispersing the grains as they were poured into the storage bin. To be absolutely sure that each mortar mix used a comparable mix of sand grains, further tests were undertaken.

When weighing out the sand for each mix, approximately 850 grams were placed into a marked plastic bag and set aside. Seven bags were collected for the seven different mortar mixes. Each bag was then individually graded using a British Standard sieve collection consisting of 2.36 mm, 1.18 mm, 0.60 mm, 0.30 mm and 0.15 mm meshes. The finest particles collected in the bottom pan are called silt. The 1.18mm mesh sieve was chosen as the maximum particle size retainer. Before each grading, the sieves were carefully cleaned to remove all trace of the previous sand.

Calculations for determining the quantities of sand passing through and retained in each sieve were made by using the following equations. The percentage of passing sand equation was written: $100 - <[(A - B)/T] \times 100> - P$ where 'A' is the weight of the sieve with the sand, 'B' is the weight of the sieve alone, 'T' is the total sum of all the sieves' weight differences, and 'P' is the sum of all previous 'percentage retained' figures for that given mix. The percentage of sand retained was computed by deducting the 'percentage passing' figure from 100. The results are shown in Table 18 and Graph 8. The respective 'percentage passing' figures are very close for each mix, showing that the sand particles were similar and evenly dispersed throughout the batches made. The different particle sizes were therefore also uniformly interspersed within the storage bin.

Graph 7

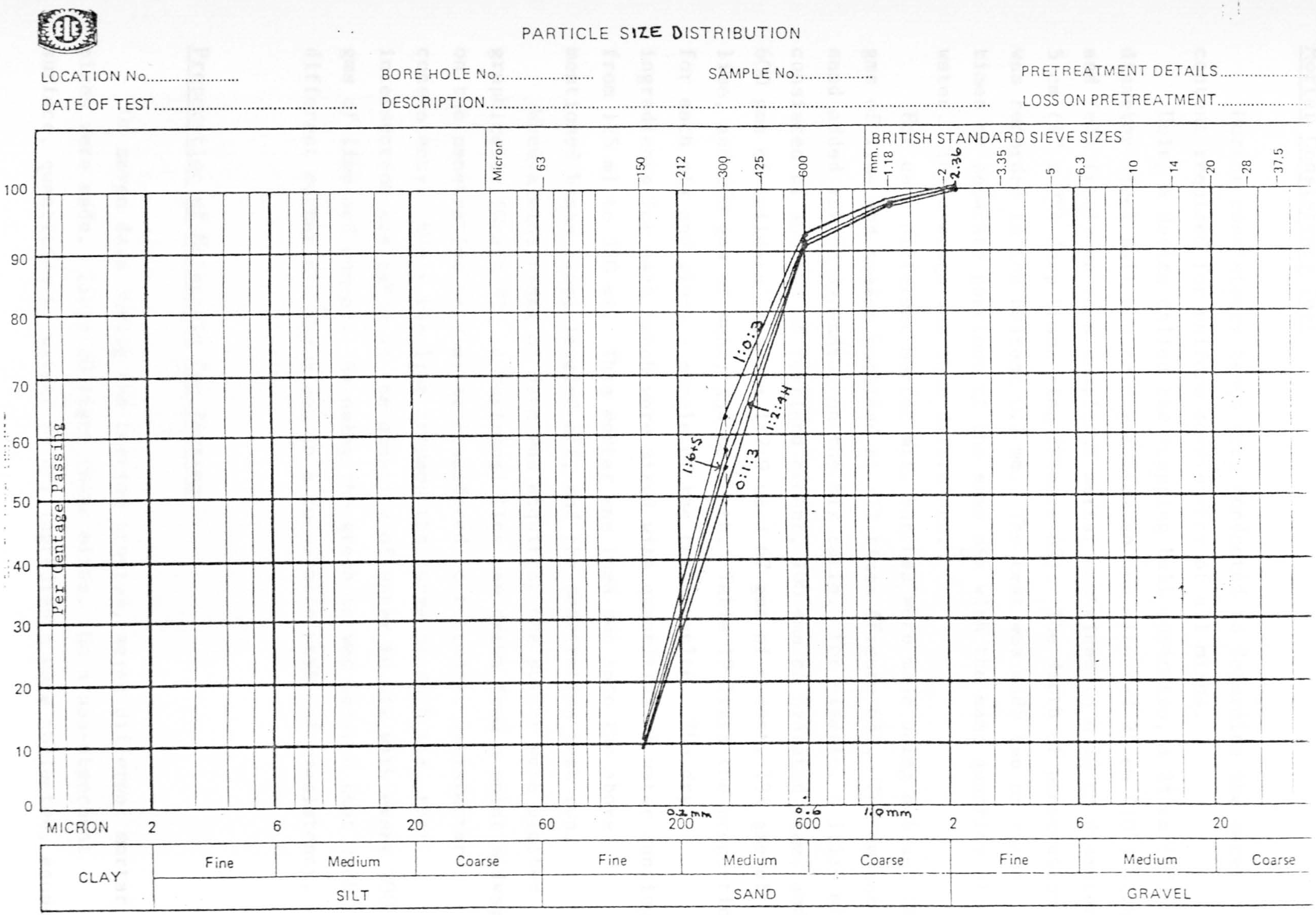


Crushing Strength in N/mm²
Age In Days
0
10
20
30
40
60
80
100
Test 1
Test 2
2-B
3-B
1-B
3-C
2-C
1-C
5-C
6-C
4-C
6-B
4-B
5-B
Note: Data points refer to cube numbers listed in Table 17.

Mortar Mix	Sieve Sizes	% Passing	% Retained
1:0:3	2.36mm	100.0	0.0
	1.18	97.8	2.2
	0.60	93.2	4.6
	0.30	63.0	30.2
	0.15	11.8	51.2
	bottom	0.0	11.8
1:1:6	2.36mm	100.0	0.0
	1.18	98.1	1.9
	0.60	93.2	4.9
	0.30	57.3	35.9
	0.15	10.4	46.9
	bottom	0.0	10.4
0:1:3H	2.36mm	99.9	0.1
	1.18	98.1	1.8
	0.60	93.0	5.1
	0.30	48.5	44.5
	0.15	9.6	38.9
	bottom	0.0	9.6
1:2:9	2.36mm	100.0	0.0
	1.18	97.6	2.4
	0.60	92.3	5.3
	0.30	50.9	41.4
	0.15	9.7	41.2
	bottom	0.0	9.7
1:2:9H	2.36mm	100.0	0.0
	1.18	97.6	2.4
	0.60	91.0	6.6
	0.30	54.3	36.7
	0.15	9.5	44.8
	bottom	0.0	9.5
1:3:12	2.36mm	99.8	0.2
	1.18	97.5	2.3
	0.60	91.1	6.4
	0.30	53.4	37.7
	0.15	9.0	44.4
	bottom	0.0	9.0
1:6+S	2.36mm	100.0	0.0
	1.18	97.6	2.4
	0.60	91.8	5.8
	0.30	57.7	34.1
	0.15	11.1	46.6
	bottom	0.0	11.1
1:0:3 test cubes	2.36mm	100.0	0.0
	1.18	97.6	2.4
	0.60	92.4	5.2
	0.30	57.8	34.6
	0.15	10.1	47.7
	bottom	0.0	10.1

Table 18: Sand Grading Test Data

The particle size distribution is evaluated in the column marked "% Retained." These figures are similar for each of the mortar mixes listed, showing that the distribution was uniform throughout the testing program. The test cubes refer to those made in mid-April for the cement grading test. The formula used to obtain the "% Passing" figures was: 100 - <[(A - B) % T] x 100> - P. The "% Retained" figures were calculated by subtracting the "% Passing" number from 100.



Graph 8: Particle Size Distribution

Mortar Consistency Test

Mortar consistency tests were conducted to determine the water content required for uniform consistency of all mixes.

Using a device called the dropping ball apparatus, a $2\frac{1}{2}$ cm (1") diameter steel ball was released from an arm situated 25 cm (10") high and fell freely on to a sample of mortar contained in a 10 cm diameter x 5 cm (4" x 2") deep brass ring (Figure 62). The depth of penetration was recorded to the nearest 0.1 mm. The test was made two or three times on separate portions of the same mix with the same quantity of water. The average was then determined.[9]

For each different mortar mix, batches were made using a fixed 200 gms of lime and cement combined at all times (Figure 63). The amount of sand added varied depending on the mix ratio. For example, a 1:1:6 mix consisted of 100 gms of Portland cement, 100 gms of hydrated lime, and 600 gms of builders' sand; a 1:2:9 used 67 gms of cement, 134 gms of lime, and 603 gms of sand; and so forth. Table 19 lists the proportions for each mix and gives a sample of the test results. The dry ingredients for each batch were mixed with quantities of water ranging from 125 ml to 320 ml. This mortar was then put into the above mentioned brass ring, leveled off, and the penetration test run.

When a wide range of data was acquired, the points were plotted graphically (Graph 9). A horizonal line was drawn from a point midway on the penetration or y-axis, considered to represent satisfactory consistency. Where the line crossed the curve of each mix, that intersection was taken as the quantity of water to mix with every 200 gms of lime and cement. By using the graph it was assured that each different mortar mix was mixed to a comparable state of consistency.

Preparation of Materials for Testing

On seven days during the testing program, seven different mortar mixes were made. Table 20 lists these mixes. On a non-absorbent surface, quantities by weight of dry ingredients were collected, enough

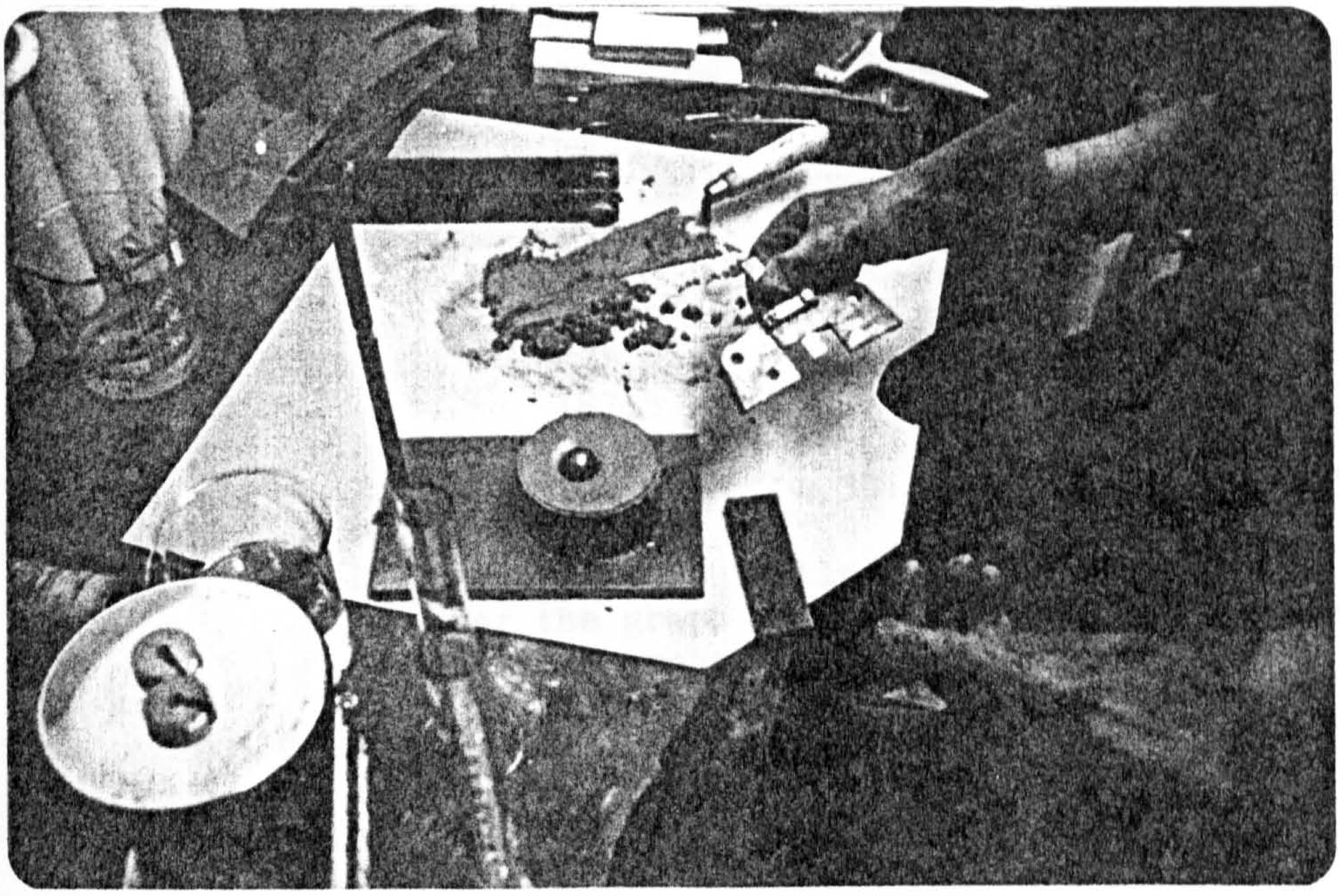


Figure 62

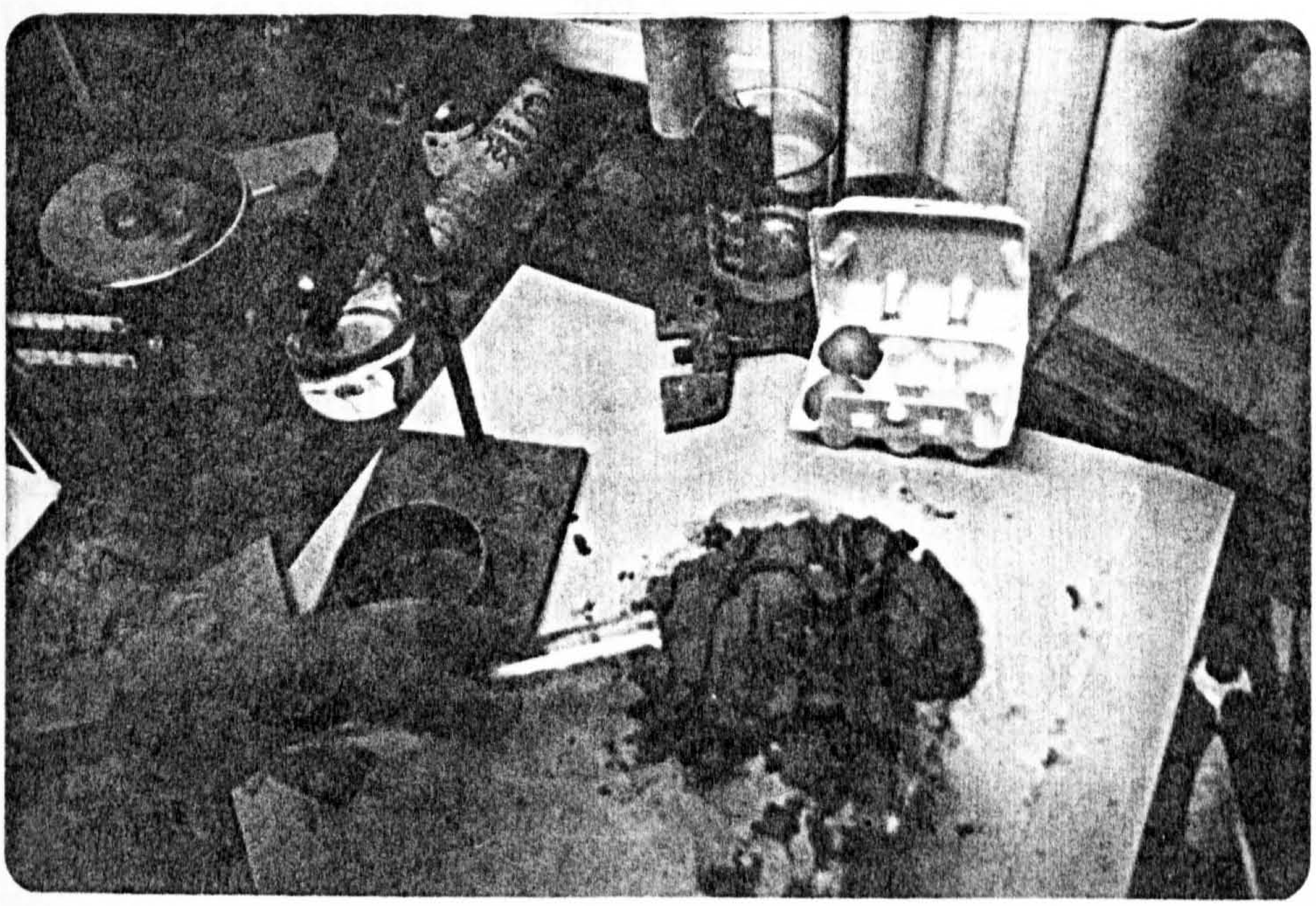


Figure 63

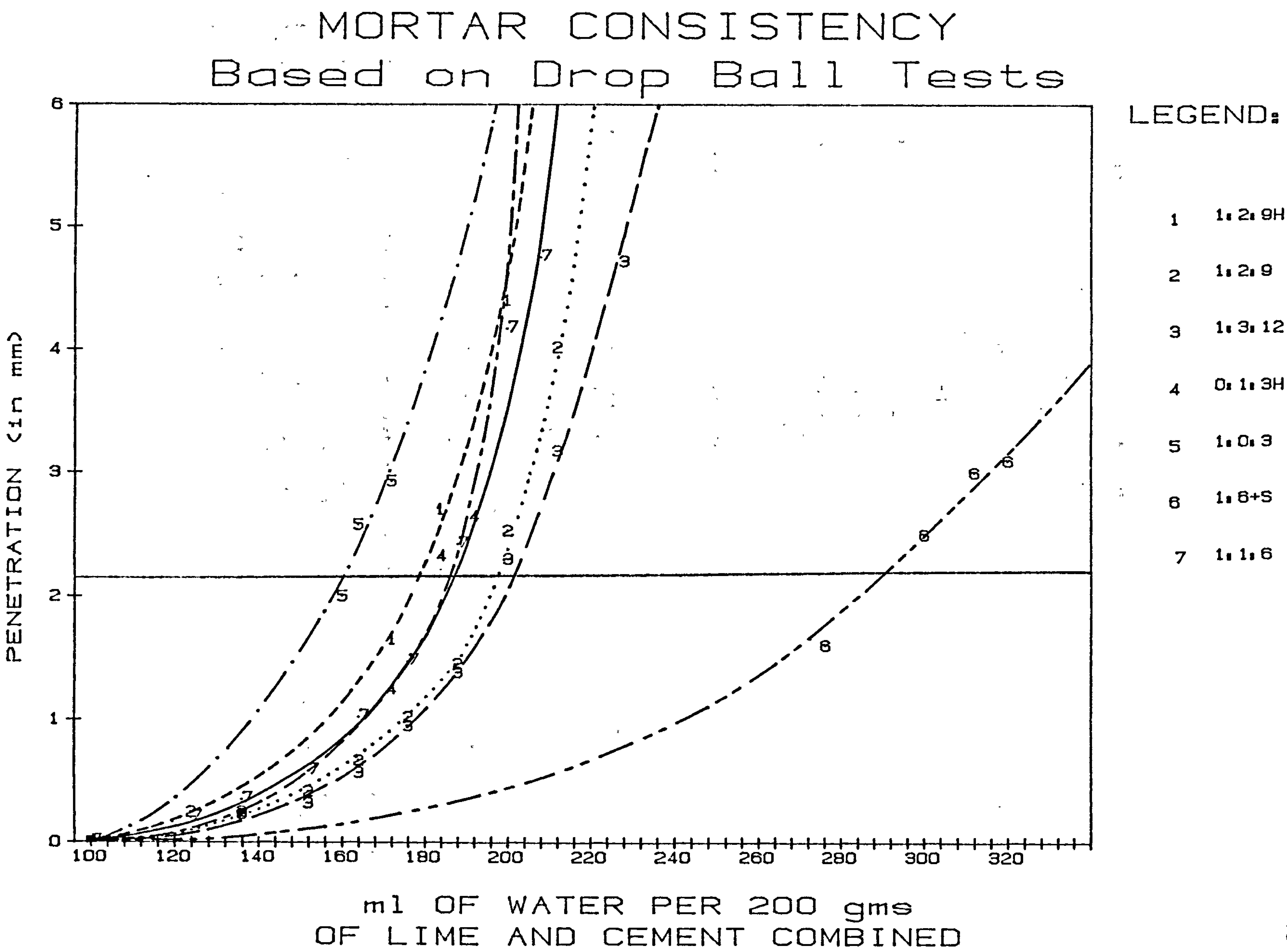
Mortar Mix Average	Proportions	Water Used	Penetration			
1:1:6	100:100:600gms	125.0ml	0.15	0.25	0.20mm	0.20mm
		137.5	0.30	0.35	0.40	0.35
		150.0	0.55	0.60	0.60	0.58
		162.5	0.95	1.05	1.05	1.02
		175.0	1.50	1.40	1.50	1.47
		187.5	2.65	2.30	2.30	2.42
		200.0	4.10	4.10	4.30	4.17
		207.0	4.35	4.95	4.95	4.75

Data continues listing only the quantity of water the graph specified to use per 200 gms of lime and cement.

1:0:3	200: 0 :600gms	162.5
1:1:6	100:100:600	186.7ml
0:1:3H	0:200:600	185.5
1:2:9	67:134:603	197.1
1:2:9H	67:134:603 using hydraulic lime	181.0
1:3:12	50:150:600	202.5
1:6+S	200: 0 :1200 + 0.5ml of Rendaplas	294.0

Table 19: Mortar Consistency Test Data

Like the mortar mixes, each set of proportions lists the dry ingredients in the following order: Portland cement:hydrated lime:builders' sand. The hydraulic lime replaces hydrated in the case of 1:2:9H and the air entraining agent, Rendaplas, also replaces the hydrated lime.


MORTAR CONSISTENCY
Based on Drop Ball Tests
PENETRATION (in mm)
0
1
2
3
4
5
6
100
120
140
160
180
200
220
240
260
280
300
320
ml OF WATER PER 200 gms
OF LIME AND CEMENT COMBINED
LEGEND:
1 1:2:9H
2 1:2:9
3 1:3:12
4 0:1:3H
5 1:0:3
6 1:6+S
7 1:1:6

GRAPH 9

Mortar Mix	Ingredients Used	Quantities
1:0:3	Portland cement	5,148.0 gms
	Builders' sand	15,444.0 gms
	De-ionised water	4,182.5 ml
1:1:6	Portland cement	2,574.0 gms
	Hydrated lime	2,574.0 gms
	Builders' sand	15,444.0 gms
	De-ionised water	4,804.5 ml
0:1:3H	Hydraulic lime	5,382.0 gms
	Builders' sand	16,146.0 gms
	De-ionised water	4,992.0 ml
1:2:9	Portland cement	1,716.0 gms
	Hydrated lime	3,432.0 gms
	Builders' sand	15,444.0 gms
	De-ionised water	5,047.5 ml
1:2:9H	Portland cement	1,716.0 gms
	Hydraulic lime	3,432.0 gms
	Builders' sand	15,444.0 gms
	De-ionised water	4,610.0 ml
1:3:12	Portland cement	1,239.0 gms
	Hydrated lime	3,717.0 gms
	Builders' sand	14,868.0 gms
	De-ionised water	5,018.0 ml
1:6+S	Portland cement	3,146.0 gms
	Synthetic: Rendaplas	7.8 ml
	Builders' sand	18,876.0 gms
	De-ionised water	4,624.5 ml

Table 20: Mortar Mixes Used in Testing Program
These mixes were selected based on A.S.T.M. and B.S. standards and on recommendation from architects in the field. The specified proportions in the three-part ratio shown stand for the quantity of Portland cement, lime, and sand used in each instance. For example, the 1:1:6 mix is composed of 1 part Portland cement, 1 part lime, and 6 parts sand. In the 1:6+S, the lime has been replaced by Rendaplas, an air entraining agent. The 'quantities' column gives the weights used to produce 10 cylinders and 6 cubes.

to fill six cube moulds and ten cylinder moulds (Figures 64 - 66). They were thoroughly mixed before de-ionised water was added and then thoroughly mixed again in a wet state (Figure 67). The prepared cube and cylinder moulds were then filled with mortar: a portion was added and tamped down with a stainless steel rod to eliminate air pockets, then more of the mix. This continued until the moulds were filled and leveled. All moulds were set aside to harden for approximately 20 hours (Figure 68).

After that period of time, the cubes were removed from their moulds and the latter thoroughly cleaned to remove any stuck mortar particles and remaining grease (Figure 69). The bases were detached from the cylinder moulds, but the mortar samples themselves remained in the moulds (Figure 70). The top of each cube and cylinder sample was painted, using a water-proof paint, with the mix name and a sample number. The entire lot was then submerged in a bin of room-temperature tap water for a period of 13 days (Figure 71).

Upon removal from the water, the cylinders were released from their moulds by the process described above on page 196. Immediately afterwards, both the cylinders and the cubes were weighed and moved to drying racks for another 14 days. The total curing time was 28 days: one day to air harden after mixing, 13 to harden under water, and an additional 14 days of air drying. While Lenczner and Neville both aged their samples for 28 days, neither specifically mentioned curing them in water for one half that time.[10] Usually their samples spent all 28 days curing in air or in water, not a combination of both.

The half-water/half-air drying method was developed to aid the weaker mixes. Preliminary pre-test experimentation showed that when weaker mixes were removed from their moulds after only one day, the incidence of cracking and breakage was high. This was eliminated altogether by submerging them in water for 13 days. As hydraulic lime and cement are known to develop their strength by contact with water, the water curing enabled the weaker mixes to gain strength and thus, survive intact for testing.[11]

The samples were removed from the water and given 14 days to air dry for two reasons. First, it was important that the measurement of

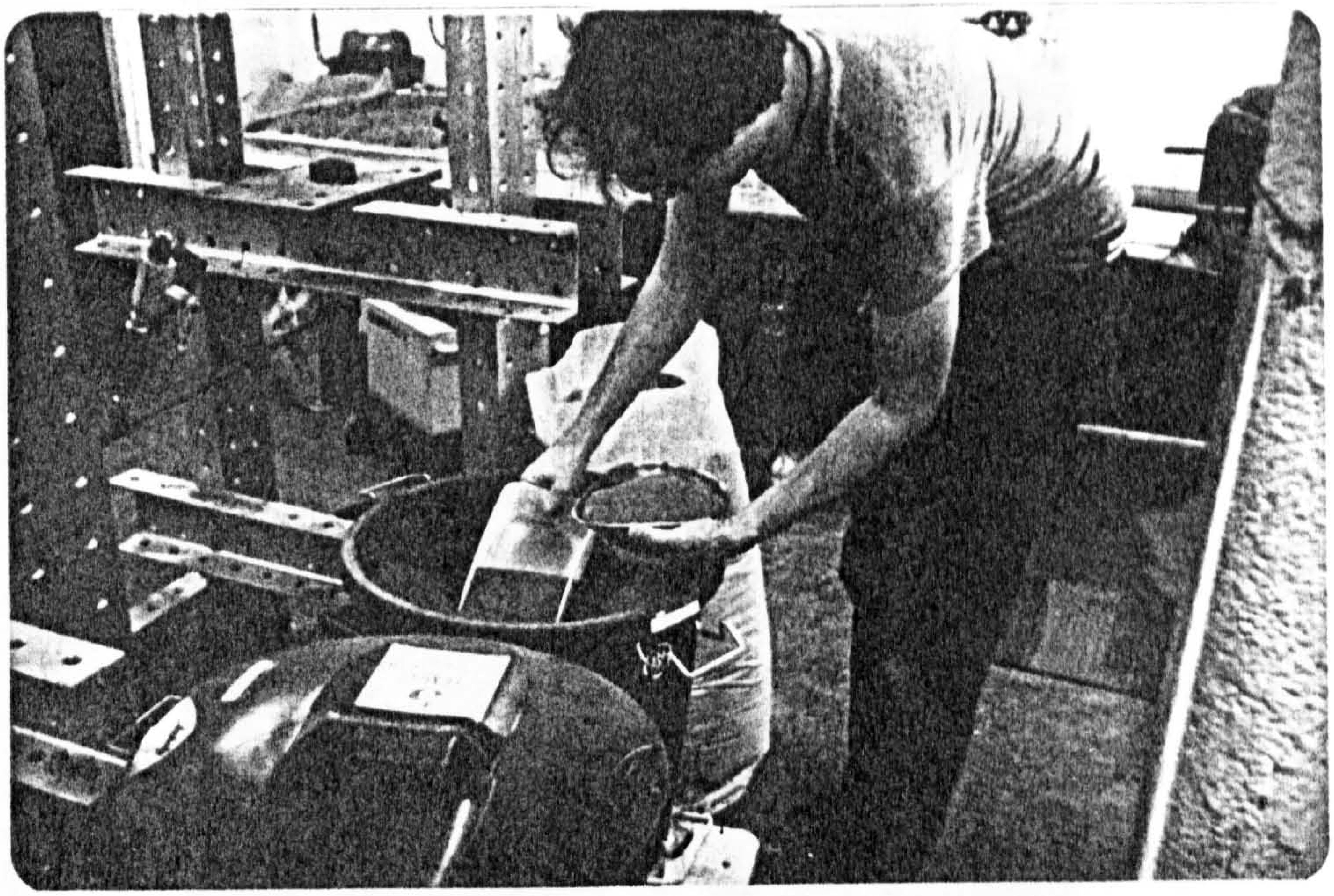


Figure 64

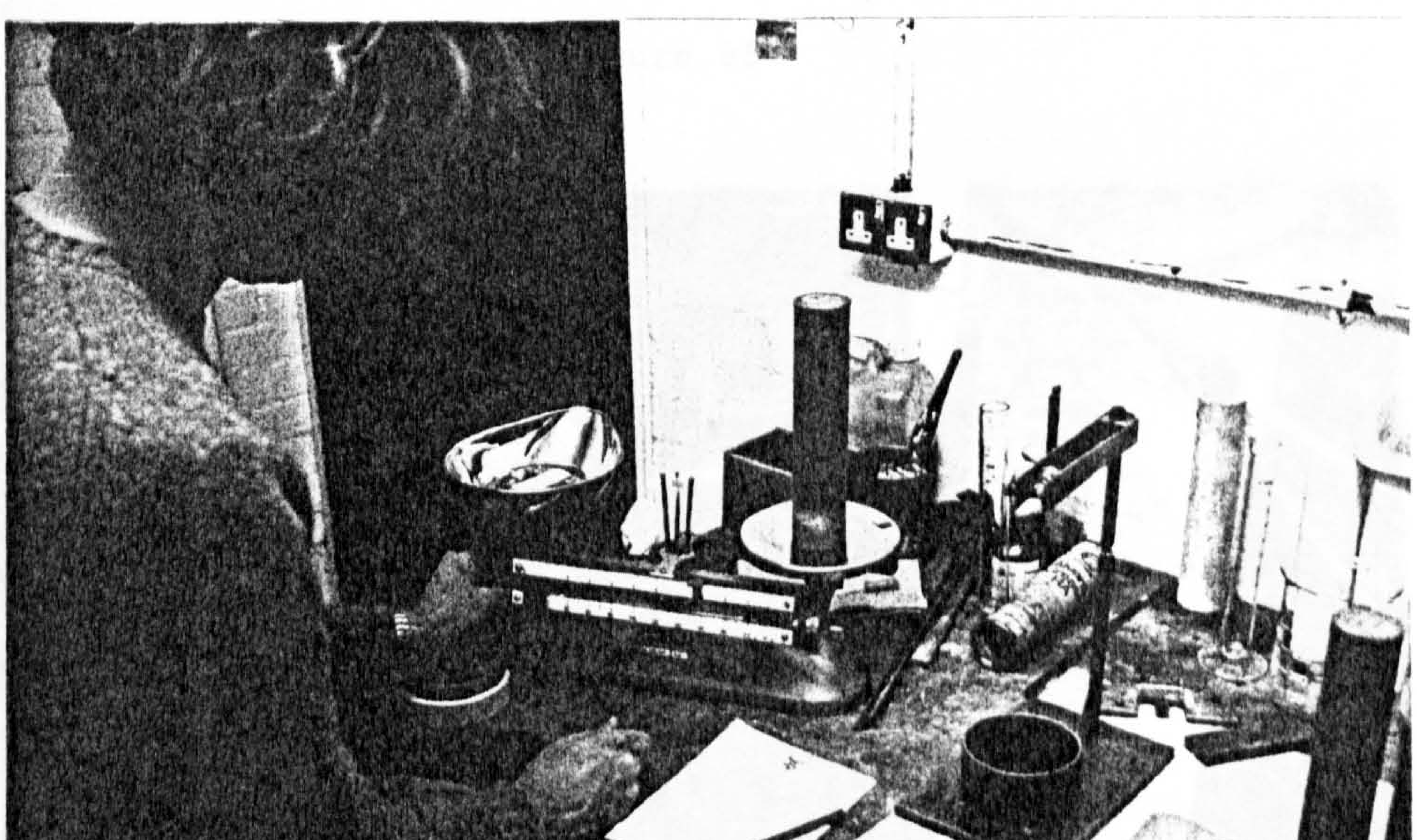


Figure 65

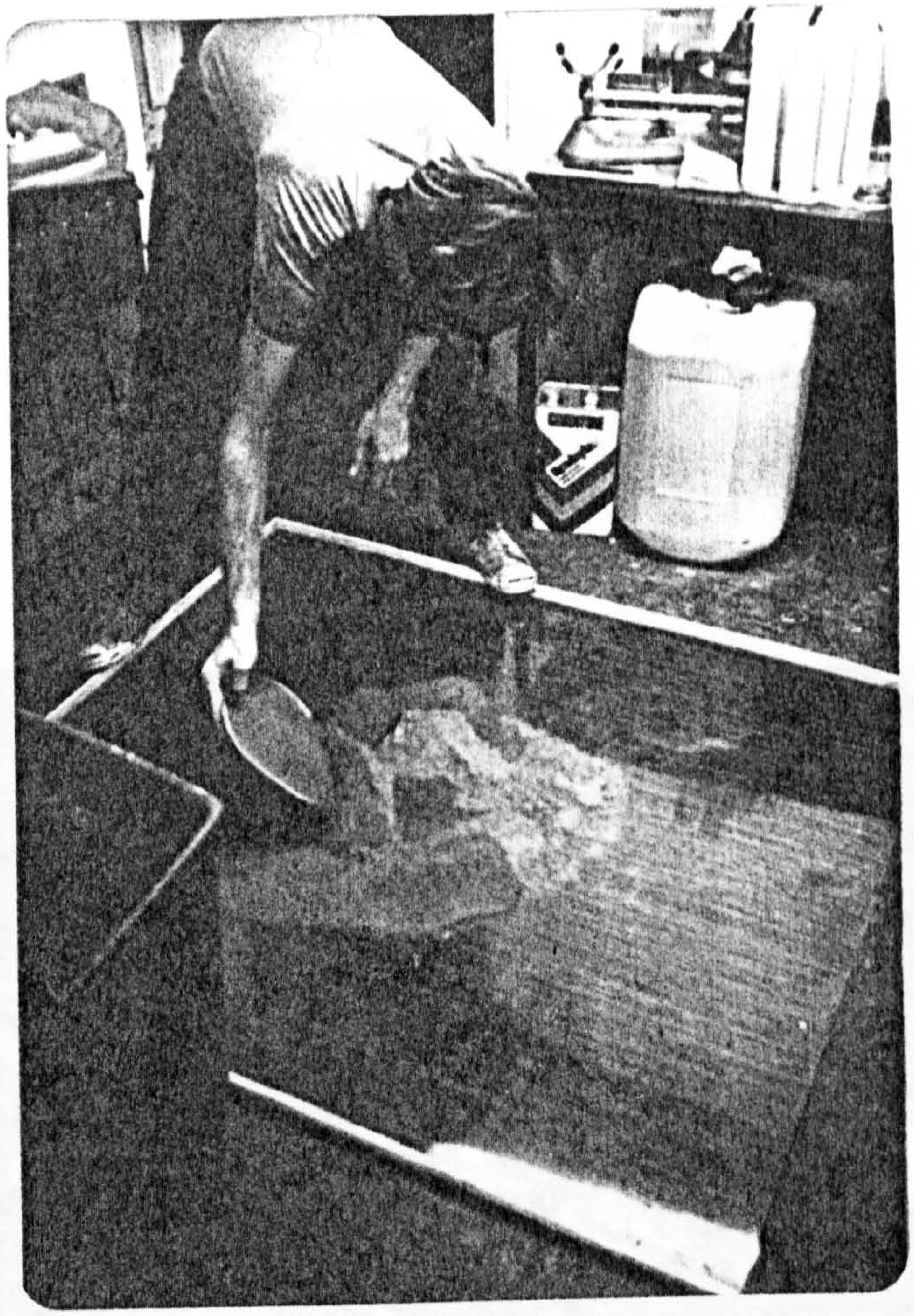


Figure 66

Figure 67

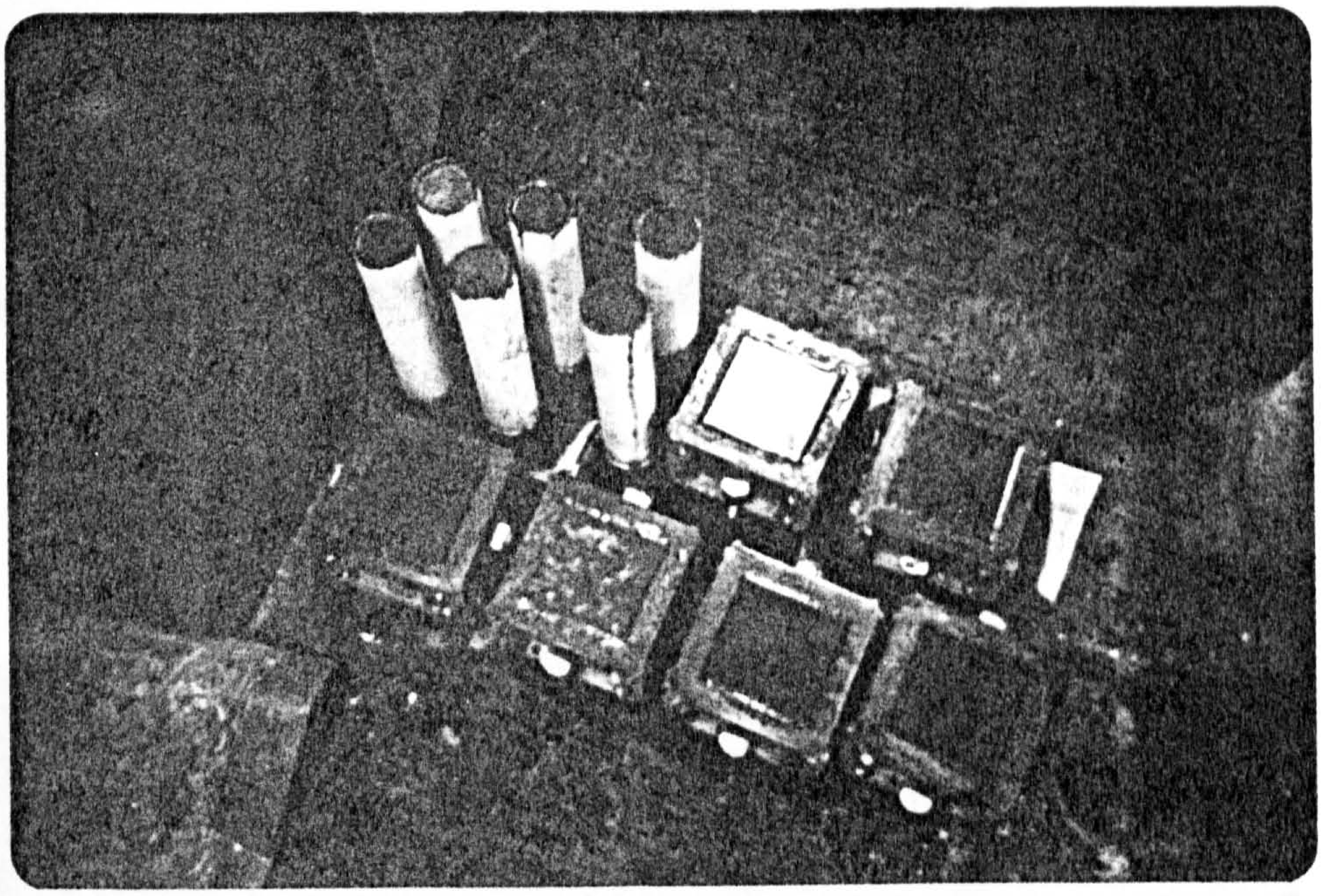


Figure 68

Figure 69

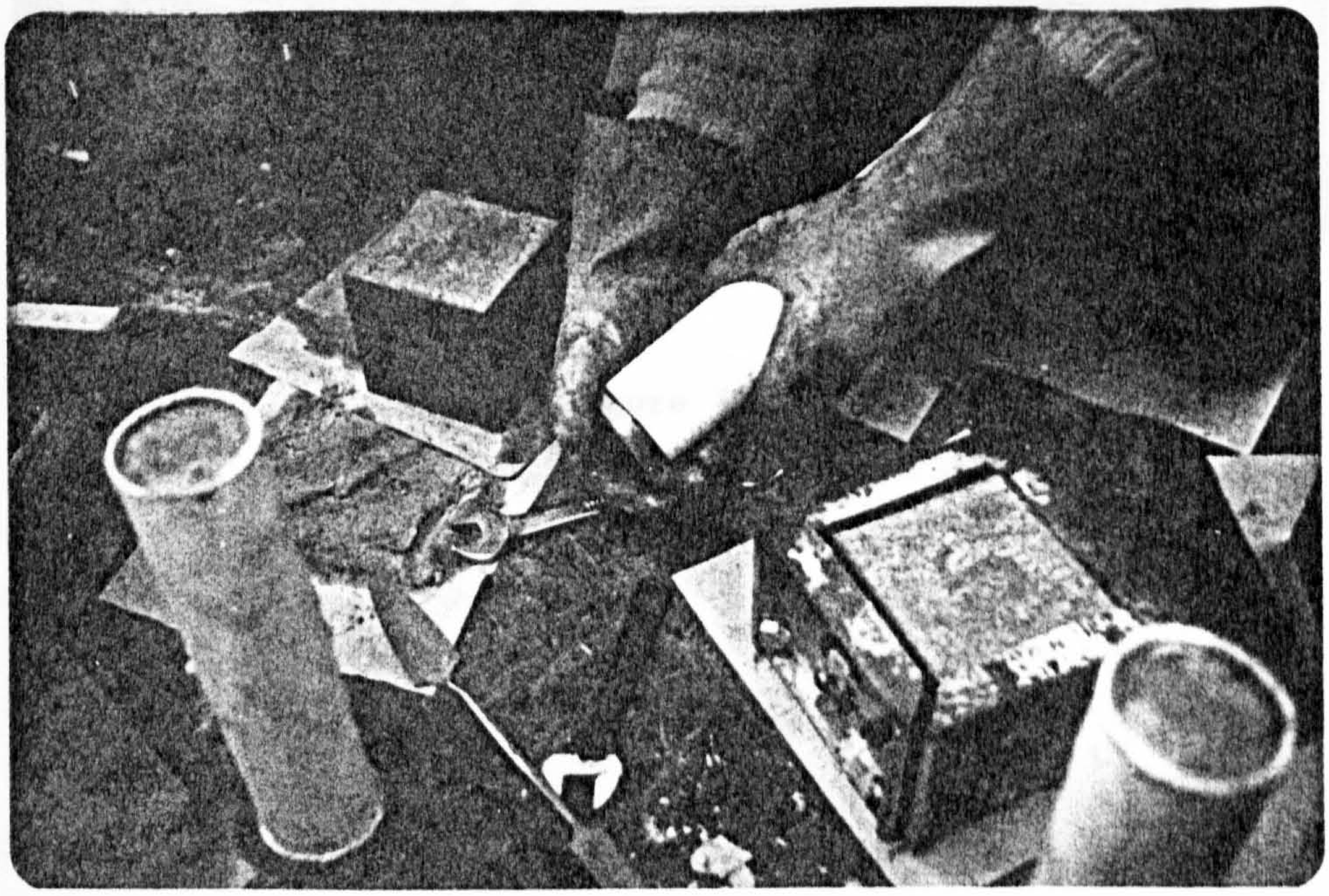


Figure 70

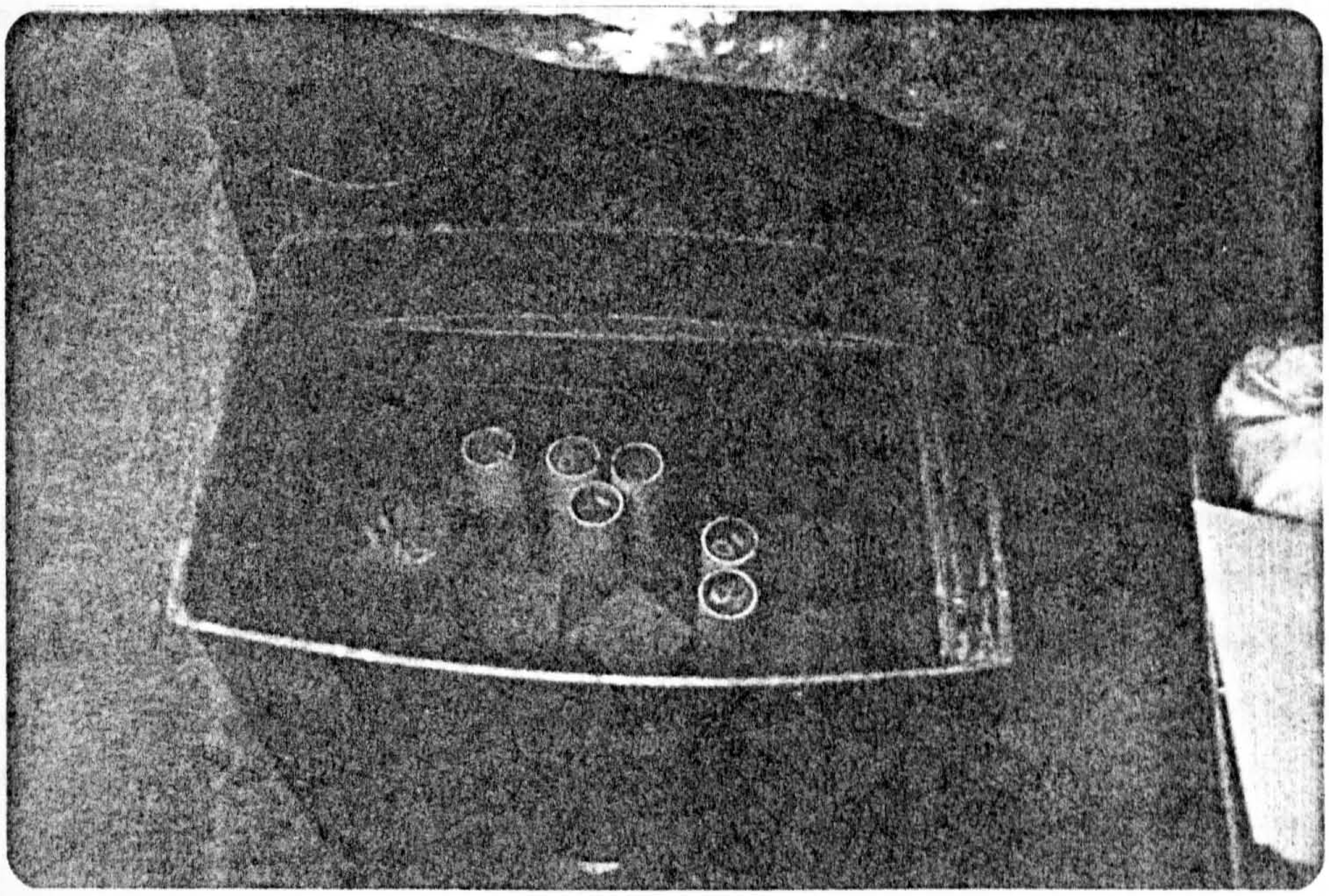


Figure 71

creep be free of as many outside factors as possible. Mixes tested directly upon removal from the water might show a greater shrinkage than creep, and therefore creep would be difficult to measure. A period of air drying was necessary to remove this possibility.

Secondly, air drying was necessary for Demec gauge pinhole discs to be attached to the cylinders. Within the first 48 hours of removal from their moulds, each cylinder had two discs epoxied near its ends. These discs could not be epoxied earlier than 24 hours because the cylinders were still too wet to allow the epoxy to adhere. Once the epoxy had dried completely and pinhole discs had no chance of slipping, daily shrinkage and weight recordings were taken. This permitted shrinkage to be closely watched and by the time the day for loading arrived, the shrinkage curve was relatively level.

The purpose of the Demec gauge and pinhole discs was to accurately monitor very small changes in linear dimension, whether such changes be caused by shrinkage or creep. A Demec gauge has two pins, one fixed and one movable, the movable pin connected to a dial that shows linear changes of dimension in units of microstrain. In use, the gauge was manually engaged with the two pinhole discs mounted on the mortar cylinder and the dial's reading recorded on a data sheet. Readings were taken to the nearest $\frac{1}{2}$ division, where 1 division = 10 microstrain or 1×10^{-5}.

Controls

Controls are a vital part of any experimentation. The experimental program was fundamentally designed to measure creep, but not all mortar samples were actually tested for creep behavior. The controls, those samples not subject to creep testing, were necessary to provide information about strength and shrinkage, so that the experiments could be correctly designed and the results correctly analyzed. The mortar controls used here took two forms: cylinders and cubes. Both were part of the ten cylinders and six cubes made from each mix batch and received identical curing and aging treatment to those cylinders destined for creep testing.

At 28 days of age, four of the ten cylinders were removed to the creep machines for testing. The remaining six served as controls on shrinkage of the cylinders and continued to age for periods up to 153 days depending on the schedule. Two of these were later creep tested while the last four cylinders continued as controls.

On five or more days a week throughout the testing program, readings were taken of shrinkage and weight-loss. They provided important data on shrinkage in mortar up to 179 days old and how it varies from mix to mix.[12] The readings were also important in determining creep strain: creep strain equals total strain (measured under load) minus shrinkage (measured in controls). The cubes, while serving in the cement control test, also gave the strength of mixes at the dates each of the creep tests was started. The stress applied in creep tests could, therefore, be related to the crushing strength of the mix.

Creep Testing Procedure

For creep testing, the ends of the mortar cylinders were capped with 1¼ cm (½") of gypsum stucco or Plaster of Paris as the cylinders were placed between the platens at one end of the loading lever. Wedges of wood under the bottom platen prevented movement for a period of 12 - 24 hours prior to loading and allowed the caps to gain full strength. The employment of plaster caps overcame any roughness of the ends of the cylinders and allowed the compressive load to be evenly distributed across the top and bottom surfaces of the cylinders.

Two hours prior to loading, three cubes of the same mix were crushed and the load to be applied in the creep tests calculated from the average crushing strength. For the testing commencing at 28 days, 1/8th and ¼th of the crushing strength were determined for two each of the four cylinders to be loaded. These fractions were chosen because the enormous strength differences between some of the mixes meant that the compressive force had to be based on fixed fractions of their own crushing strength. For example, using Table 21, 1:0:3 had an average strength of 25.15 N/mm^2, but 0:1:3H only had a strength of 1.07 N/mm^2. If all cylinders, regardless of mix, were subject to the same absolute compressive forces, those forces would necessarily have to be small to avoid destroying the samples of weaker mixes. Under that limitation the samples of stronger mixes would barely register creep.

The calculations for determining the required compressive force were as follows. For example, on the 28th day, three 1:0:3 cubes crushed at an average of 251.5 kN. By dividing this by the cube area of 10,000 mm^2 (or about 16 sq.in.), the compressive strength was computed. 251.5 kN = 251,500/10,000 = 25.15 N/mm^2. One-quarter of this, following the above procedure, was figured and multiplied by the area of the cylinder: Pi/4 x $(50)^2$ = 1,963 mm^2. 25.15/4 = 6.2875N/mm^2; 6.2875 x 1963 = 12342.362N. These were then divided by 11 and multiplied by 0.1019 to produce answers in kilograms. The 11 is the lever ratio between the compressive force and the applied weight, as previously mentioned, and 0.1019 is the constant required to convert newtons to kilograms. 12342.362/11 = 1122.033 N x 0.1019 = 114.34 kg. Following the same steps, one-eighth of 25.15 N/mm^2 is ½ of 114.34 or 57.17 kg.

For the second set of creep tests conducted at the age of 70+ days, two cylinders of each mix were loaded at a fixed 0.70 N/mm^2 (or 0.59 N/mm^2 in the case of 1:3:12 and 0.58 N/mm^2 for 0:1:3H) as it was felt that a uniform force should be tried, regardless of strength difference.[13] The figure, 0.70 N/mm^2, was chosen as it was approximately one-third of the crushing strength of the 1:3:12 mix, a weak mix according to other data. Lack of time prevented the 1:6+S mix from being tested a second time.

Once the weights had been prepared for the cylinders in the creep machines, a reading was taken, using the Demec gauge, just prior to the load being applied. The weights were then set on the rack and the wood wedges removed; the Demec gauge was held in place and watched to record the deformation. Measurements were made at the following times after the entire load was applied: at 15 and 30 seconds, at 1, 2, 5, and 15

Mortar Mix	Age	Cube No.	Crush. Strength	Average
1:0:3	28 days	13B - 1	245.50 kN	
		13B - 2	257.00	251.50 kN
		13B - 3	252.00	25.15 N/mm^2
	91 days	13B - 4	282.00	
		13B - 5	278.00	283.34 kN
		13B - 6	290.00	28.33 N/mm^2
1:1:6	28 days	6C - 1	59.00	
		6C - 2	56.00	57.34 kN
		6C - 3	57.00	5.73 N/mm^2
	77 days	6C - 4	69.00	
		6C - 5	69.50	68.83 kN
		6C - 6	68.00	6.88 N/mm^2
0:1:3H	28 days	01B - 1	10.00	
		01B - 2	10.80	10.70 kN
		01B - 3	11.30	1.07 N/mm^2
	153 days	01B - 4	14.75	
		01B - 5	14.65	14.57 kN
		01B - 6	14.30	1.46 N/mm^2
1:2:9	28 days	9B - 1	23.00	
		9B - 2	21.40	22.13 kn
		9B - 3	22.00	2.21 N/mm^2
	109 days	9B - 4	29.40	
		9B - 5	28.20	29.47 kN
		9B - 6	30.80	2.95 N/mm^2
1:2:9H	28 days	9H - 1	59.50	
		9H - 2	60.60	58.90 kN
		9H - 3	56.60	5.89 N/mm^2
	88 days	9H - 4	78.00	
		9H - 5	75.10	77.50 kN
		9H - 6	79.40	7.75 N/mm^2
1:3:12	28 days	12C - 1	13.50	
		12C - 2	13.70	13.40 kN
		12C - 3	13.00	1.34 N/mm^2
	91 days	12C - 4	14.60	
		12C - 5	15.65	14.92 kN
		12C - 6	14.50	1.49 N/mm^2
1:6+S	28 days	SB - 1	44.80	
		SB - 2	45.00	45.00 kN
		SB - 3	45.20	4.50 N/mm^2
	70 days	SB - 4	45.50	
		SB - 5	44.20	41.97 kN
		SB - 6	36.20	4.20 N/mm^2

Table 21: Crushing Strength Data

Strength should increase with time, and this was not the case with the 1:6+S mix; it decreased. Based on the strength of the cubes, SB - 4 and SB - 5, it is believed that SB - 6 was a rogue sample, providing inaccurate data. Eliminating SB - 6, the new strength average is 44.85 kN or 4.48 N/mm^2. Thus for the 1:6+S mix, it appears as if the mortar gains its full strength by the 28th day.

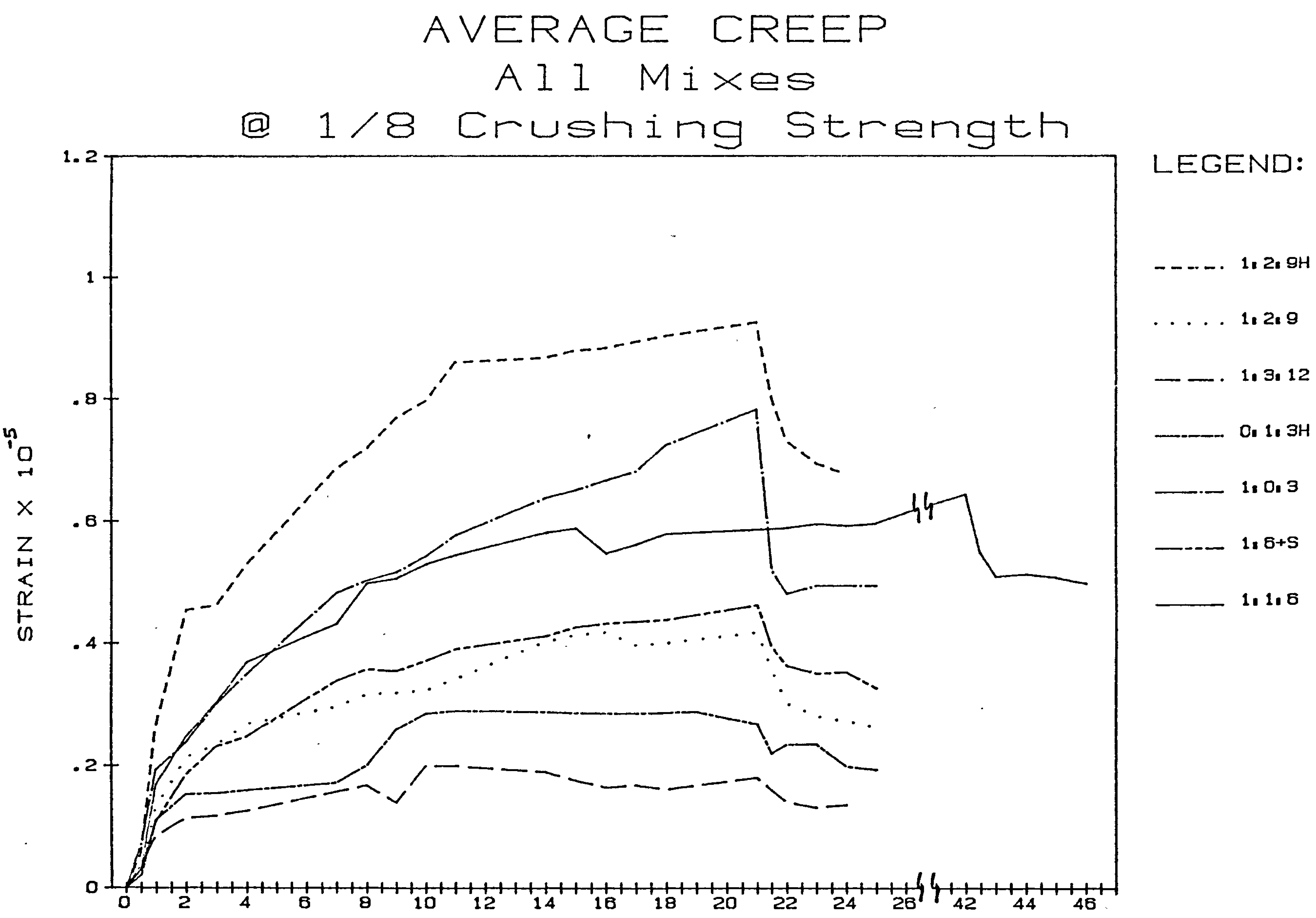
minutes, and at 1, 4, and 24 hours. A single daily reading was taken thereafter, up to 21 days.

On the 21st day, the machines were unloaded. Again, the Demec gauge recorded movement during this procedure to record the deformation. After the removal of the sample, the machine platens were cleaned and a new film of grease was applied before the next cylinders were capped and positioned. The removed cylinders were moved to the control table and their recovery was measured for the next 5 - 6 days. Readings were taken at 1, 25, and 40 minutes after unloading, and on a daily basis thereafter. The one minute reading, taken immediately after the load was applied and after it was removed, was assumed to represent the elastic deformation as recommended by Lenczner.

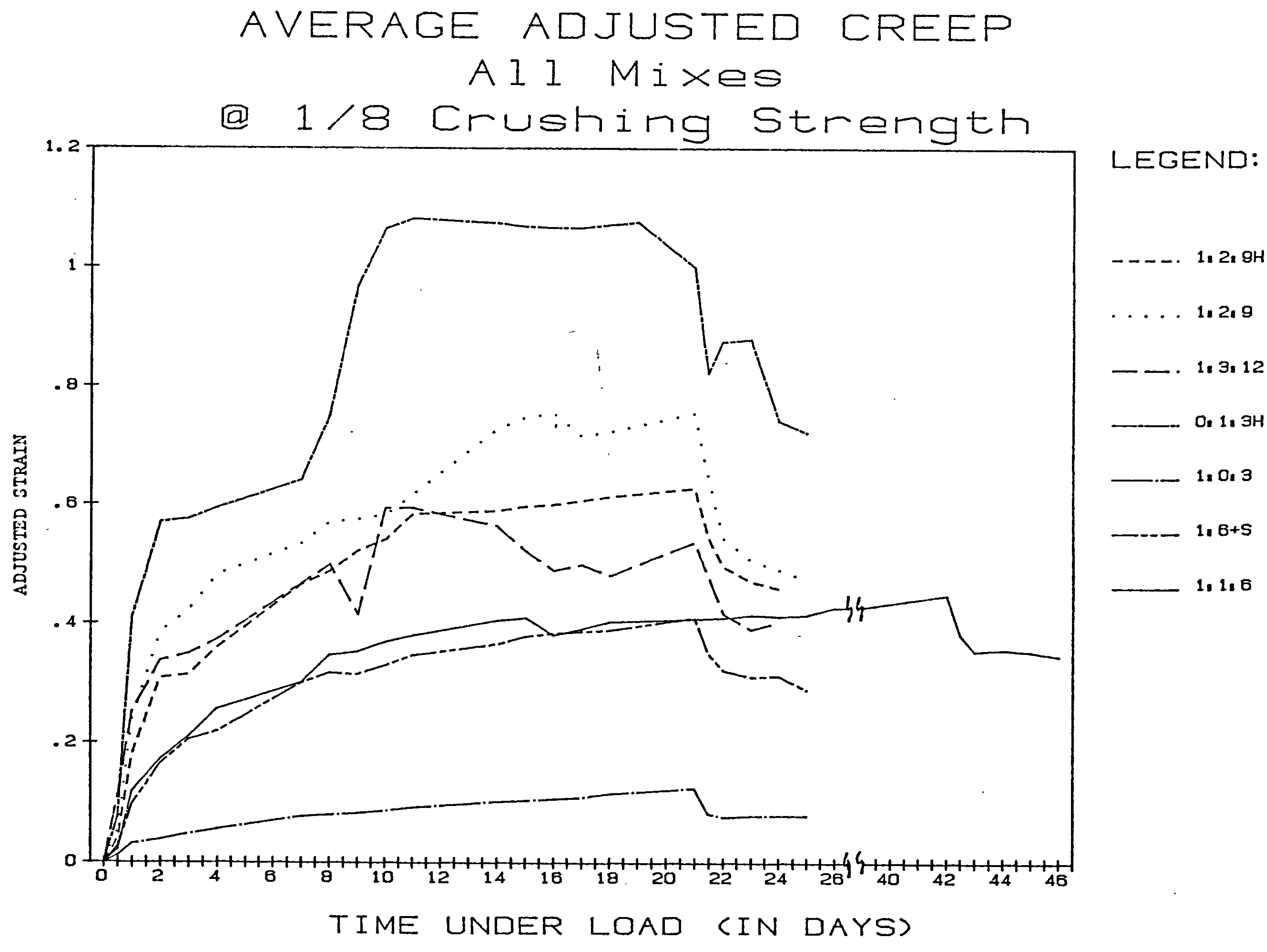
Test Results

At the beginning of this testing program it was supposed that shrinkage and creep were related to the quantity of lime in a mortar mix, in the sense that the richer the mix is in lime, the higher the values for creep and the lower the values for shrinkage. It was further supposed that the ability of masonry walls to tolerate movement derived from the occurence of creep in the mortar. These hypotheses were based on the fact that lime-rich mortar in old masonry has shown a greater tolerance of structural movements than modern cement-rich mortar. The subsequent testing of various mortar mixes provided data on creep relative to applied stress, and on shrinkage. The data compiled were then analyzed graphically to see if the initial hypotheses could be verified. Graphs were drawn of creep under three different stresses (1/8 and ¼ the crushing strength and 0.70 N/mm^2); of elastic compression and recovery; of crushing strength; of creep 21 days after loading; and of shrinkage.

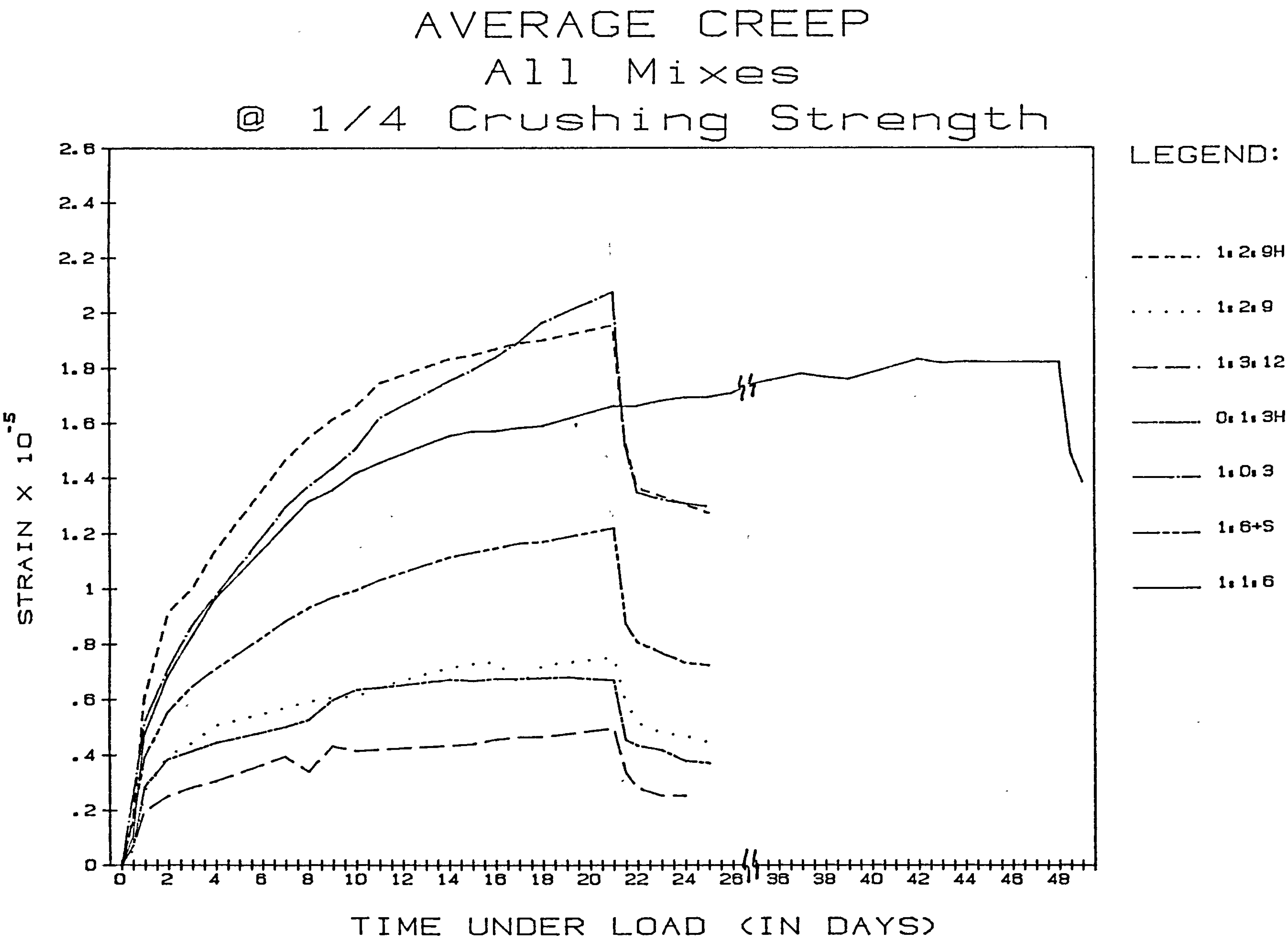
As mentioned, there were three pairs of creep tests of each mix at different stresses. The data are presented in Graphs 10 - 19. For the creep tests involving stresses of 1/8 and ¼ crushing strengths, two kinds of graphs were drawn: one showing the creep strain as calculated


AVERAGE CREEP
All Mixes
@ 1/8 Crushing Strength
STRAIN X 10^{-5}
TIME UNDER LOAD (IN DAYS)
0
.2
.4
.6
.8
1
1.2
0 2 4 6 8 10 12 14 16 18 20 22 24 26 42 44 46
LEGEND:
1:2:9H
1:2:9
1:3:12
0:1:3H
1:0:3
1:6+S
1:1:6

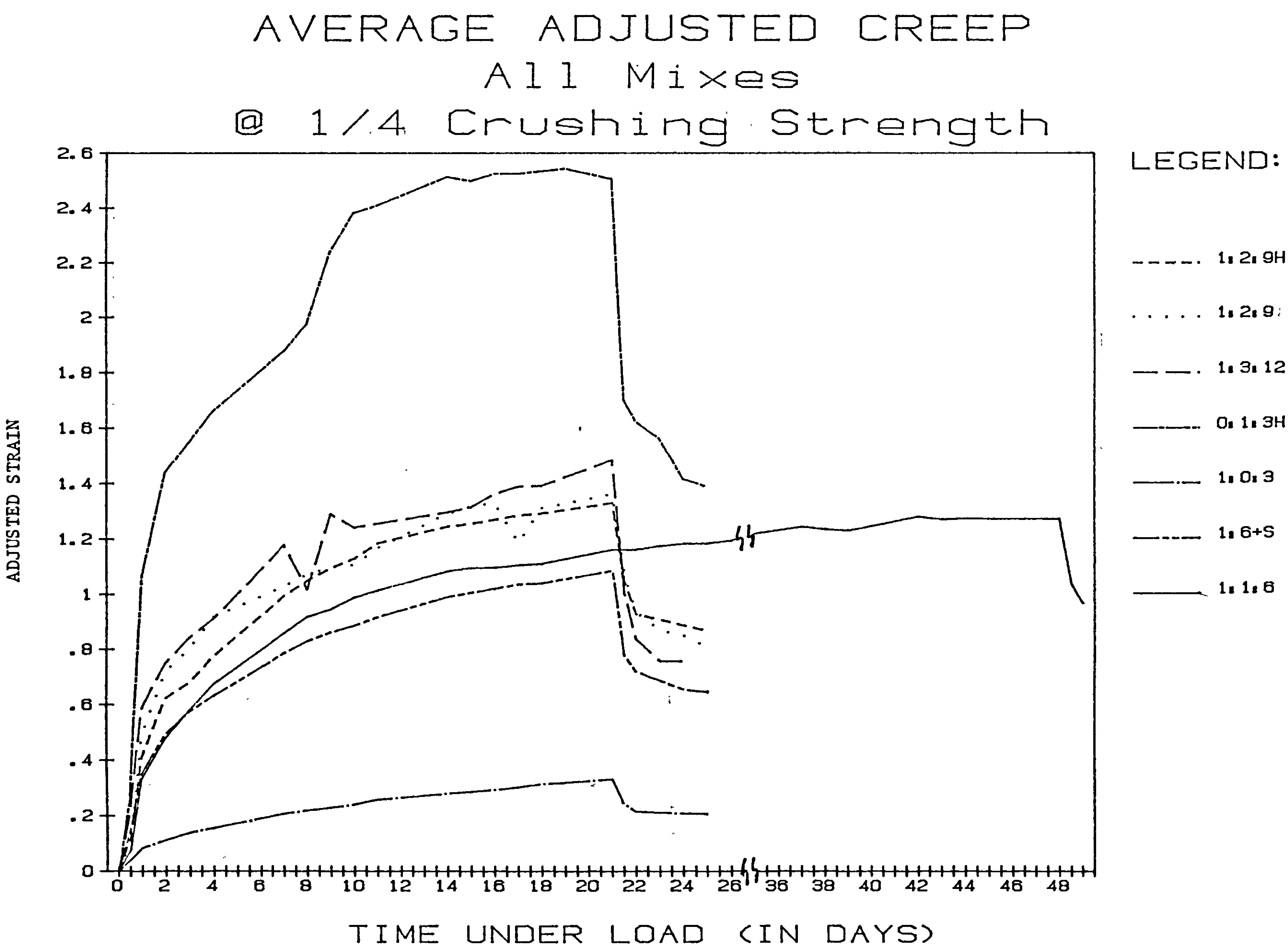
GRAPH 10


AVERAGE ADJUSTED CREEP
All Mixes
@ 1/8 Crushing Strength
LEGEND:
1:2:9H
1:2:9
1:3:12
0:1:3H
1:0:3
1:6+S
1:1:6
ADJUSTED STRAIN
1.2
1
.8
.6
.4
.2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 40 42 44 46
TIME UNDER LOAD (IN DAYS)

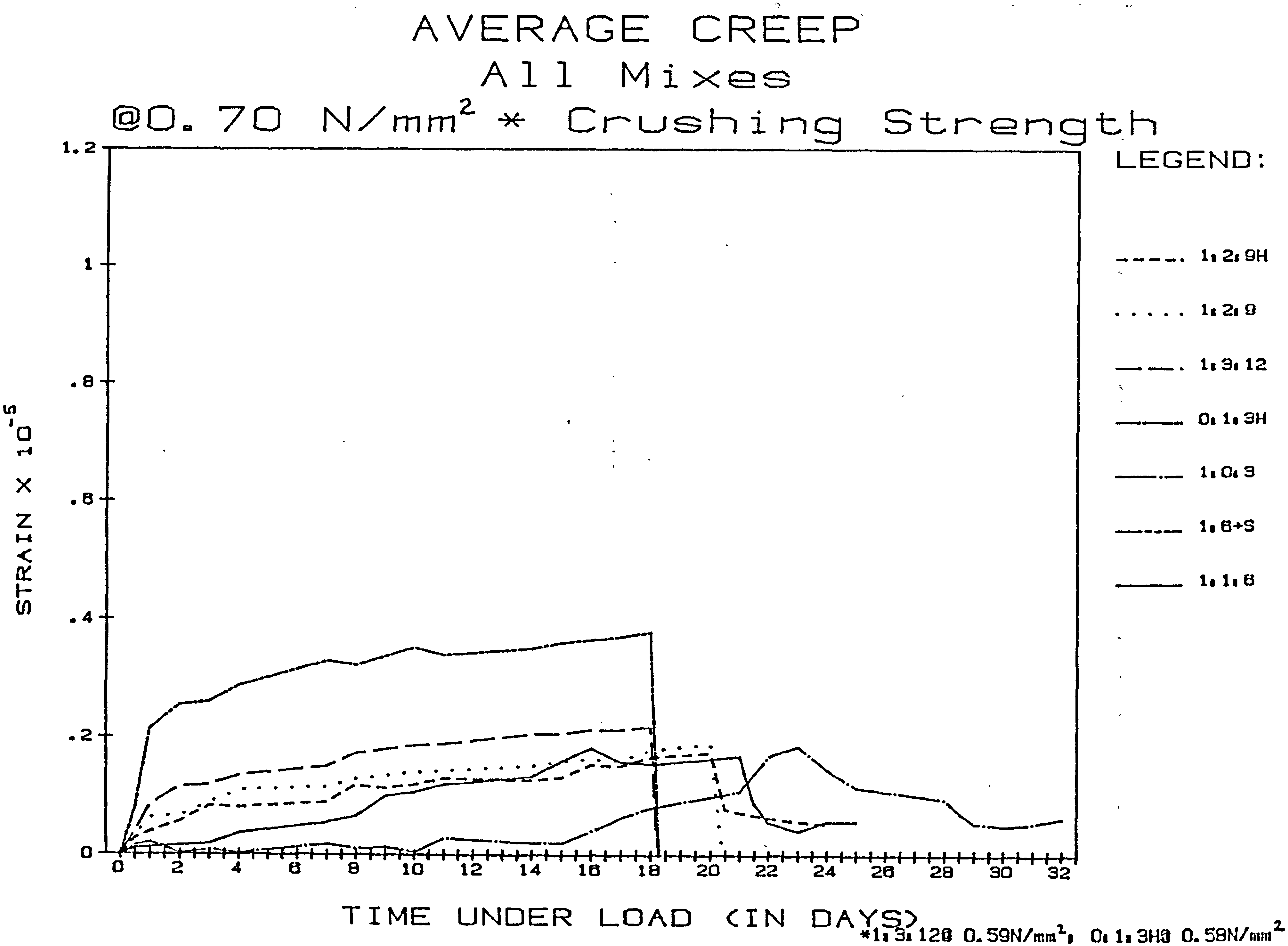
GRAPH 11


AVERAGE CREEP
All Mixes
@ 1/4 Crushing Strength
STRAIN X 10^{-5}
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 36 38 40 42 44 46 48
TIME UNDER LOAD (IN DAYS)
LEGEND:
1:2:9H
1:2:9
1:3:12
0:1:3H
1:0:3
1:6+S
1:1:6

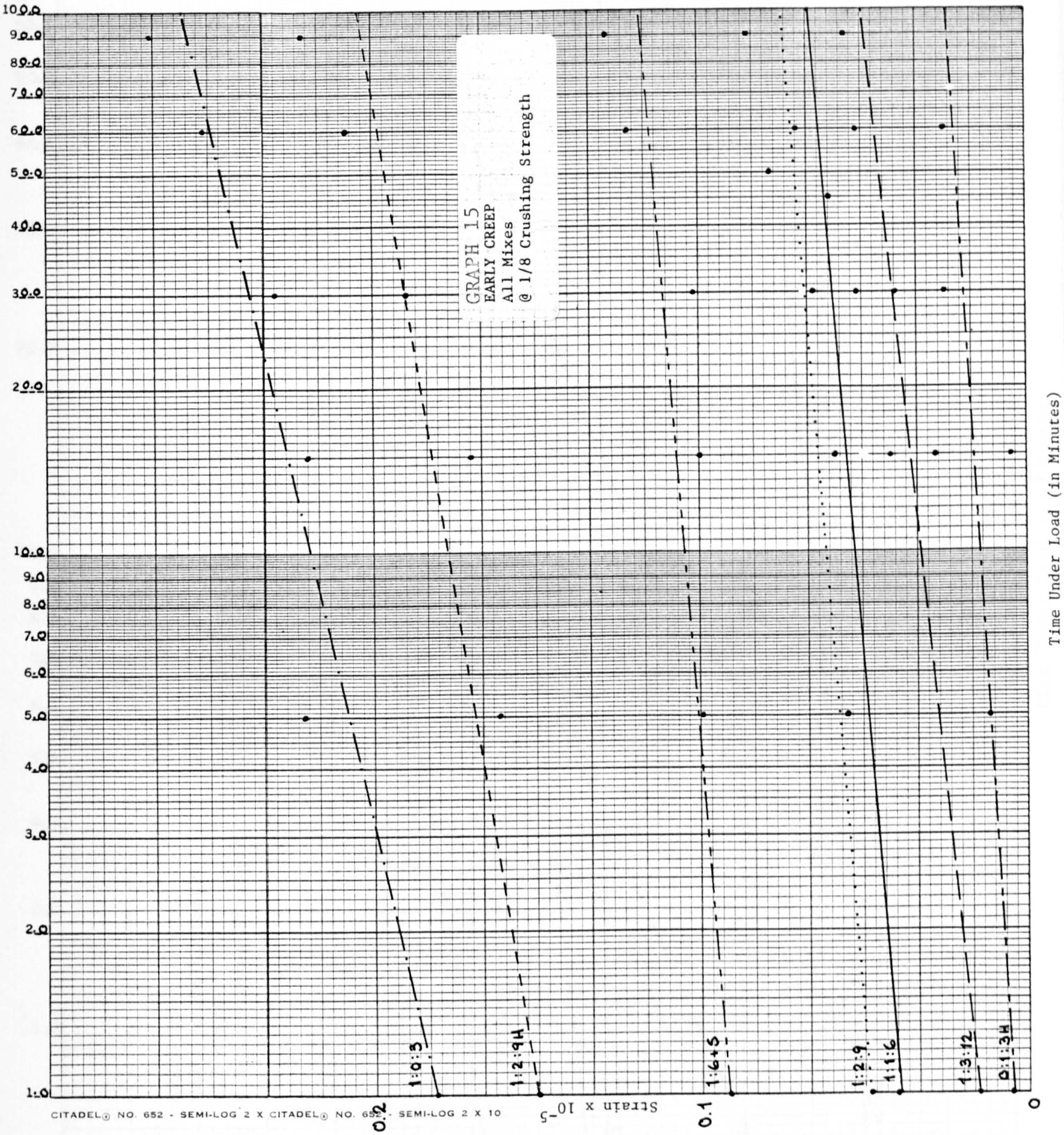
GRAPH 12

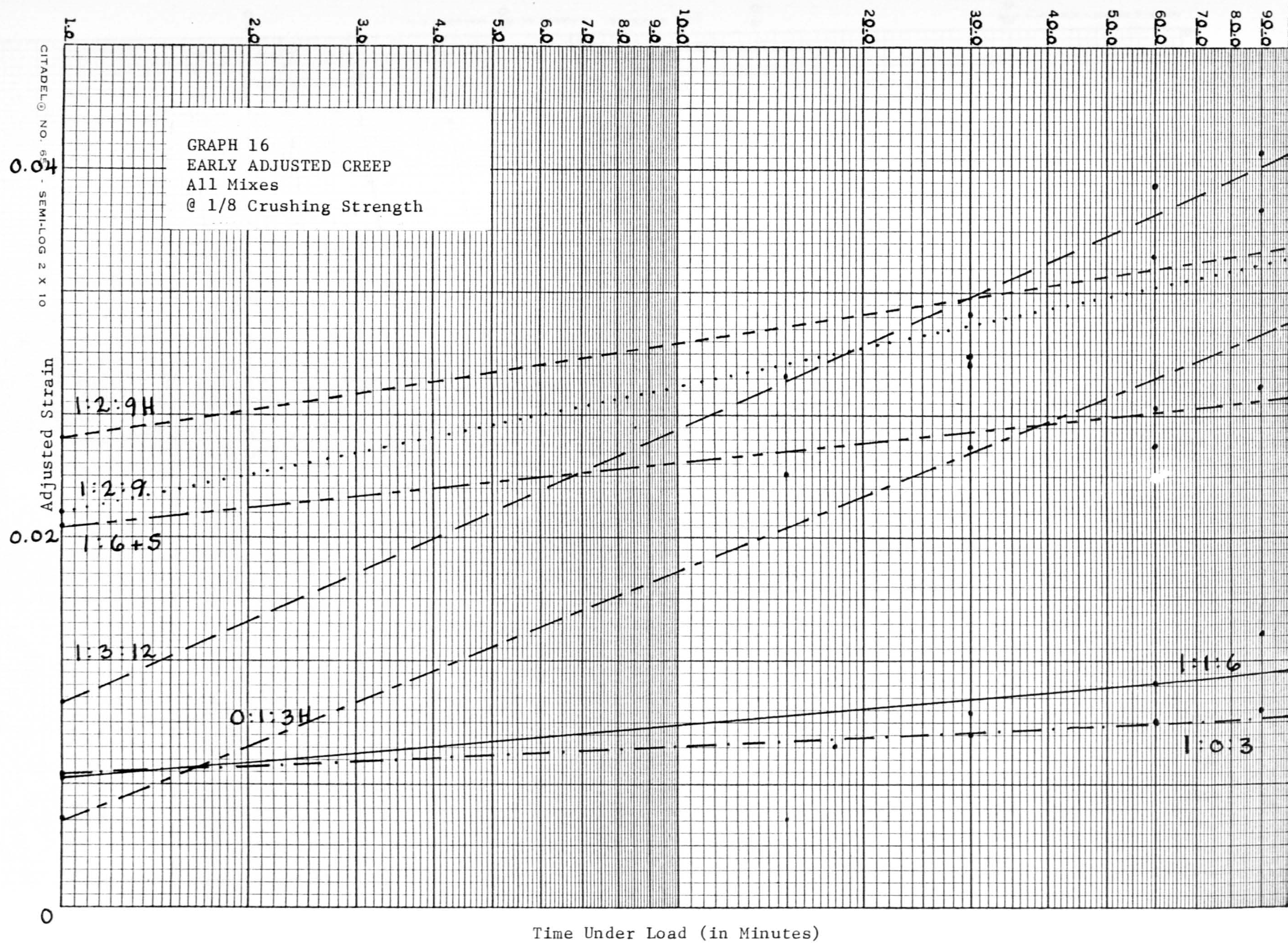

AVERAGE ADJUSTED CREEP
All Mixes
@ 1/4 Crushing Strength
ADJUSTED STRAIN
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
36
38
40
42
44
46
48
TIME UNDER LOAD (IN DAYS)
LEGEND:
1:2:9H
1:2:9
1:3:12
0:1:3H
1:0:3
1:6+S
1:1:6

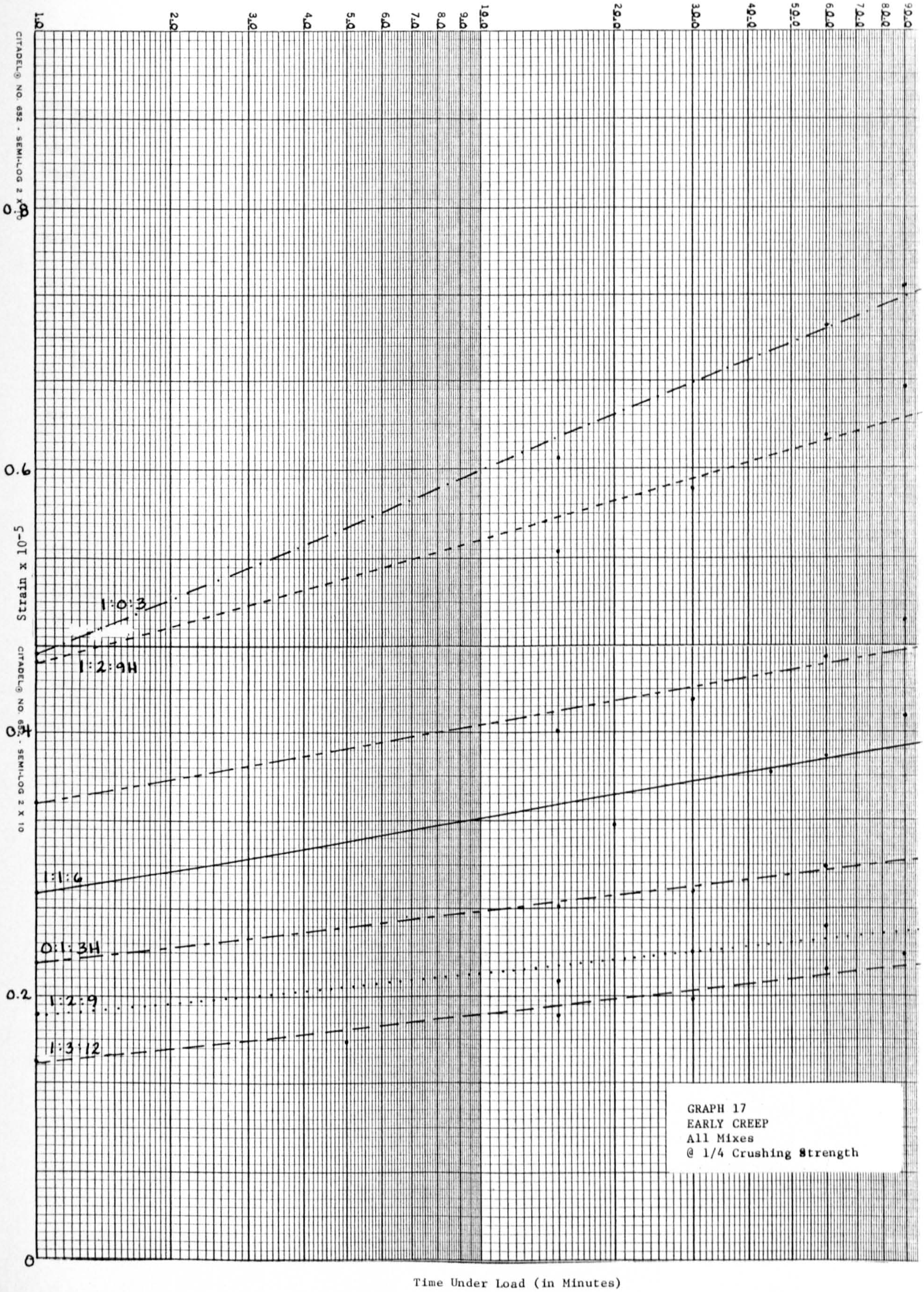
GRAPH 13

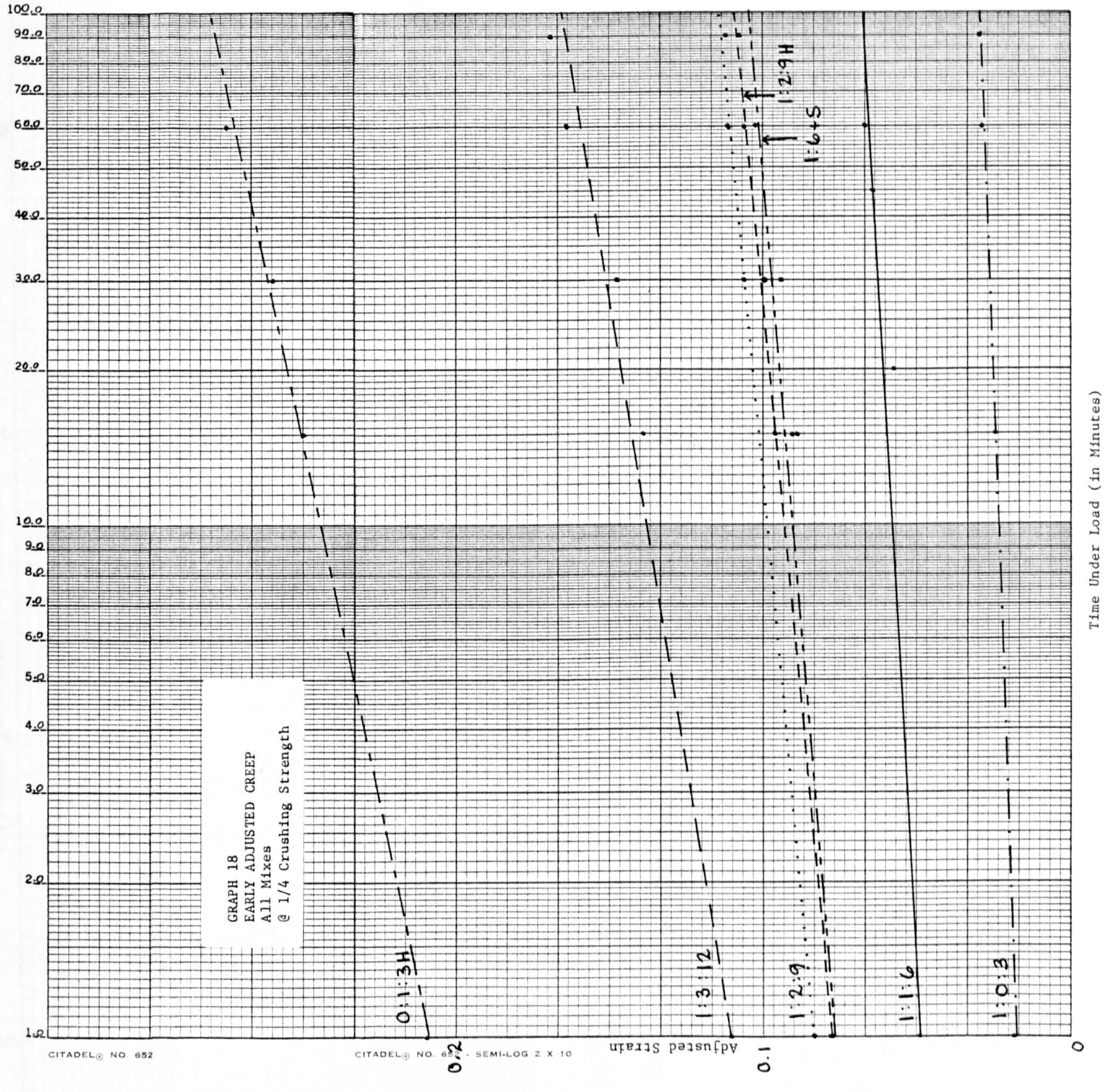

AVERAGE CREEP
All Mixes
@0.70 N/mm² * Crushing Strength
LEGEND:
1:2:9H
1:2:9
1:3:12
0:1:3H
1:0:3
1:6+S
1:1:6
STRAIN X 10⁻⁵
1.2
1
.8
.6
.4
.2
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
TIME UNDER LOAD (IN DAYS)
*1:3:12@ 0.59N/mm²; 0:1:3H@ 0.58N/mm²

GRAPH 14

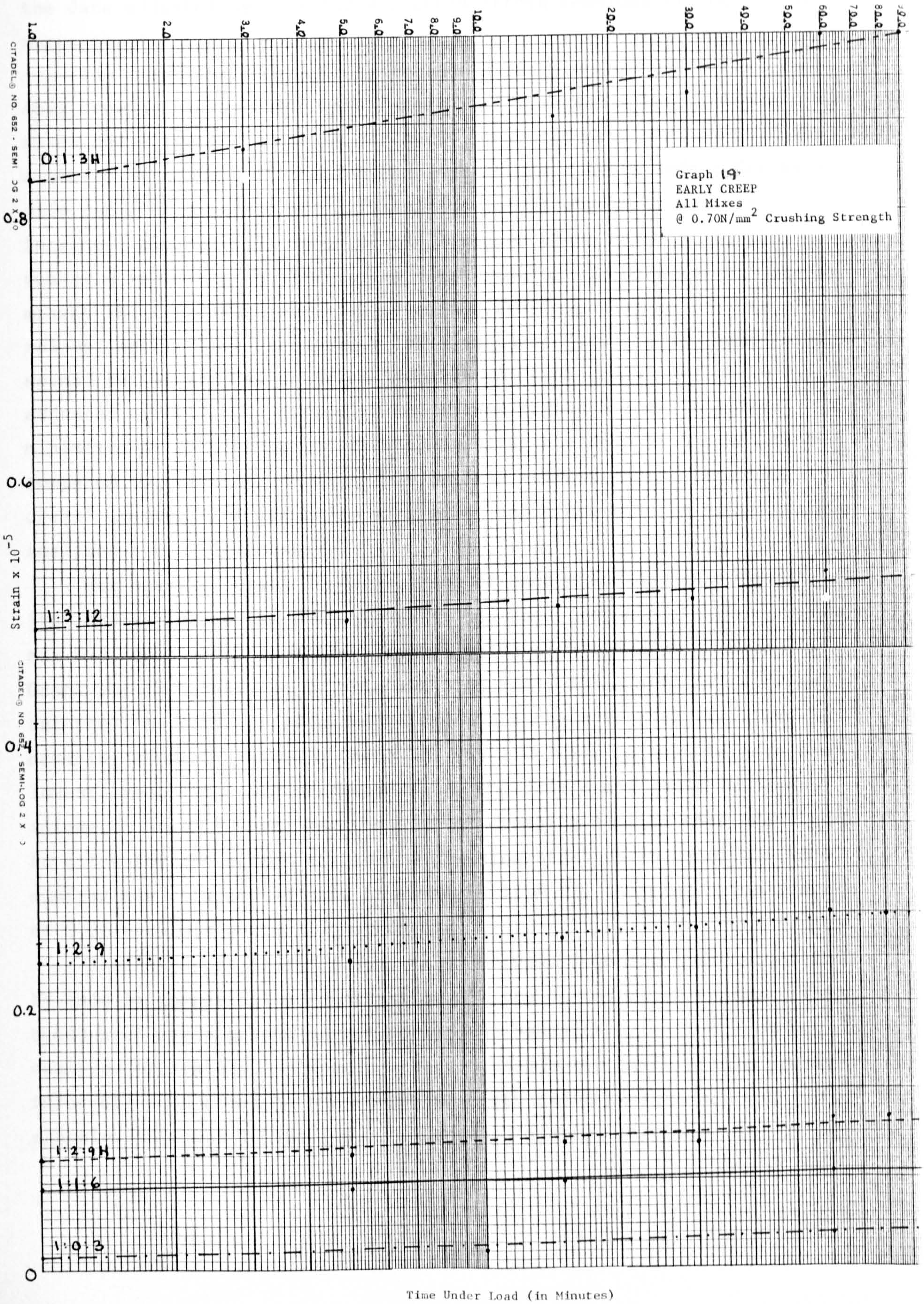

GRAPH 15
EARLY CREEP
All Mixes
@ 1/8 Crushing Strength
Time Under Load (in Minutes)
Strain x 10^{-5}
0.2
0.1
0
1:0:3
1:2:9H
1:6+5
1:2:9
1:1:6
1:3:12
0:1:3H
CITADEL NO. 652 - SEMI-LOG 2 X CITADEL NO. 652 - SEMI-LOG 2 X 10


GRAPH 16
EARLY ADJUSTED CREEP
All Mixes
@ 1/8 Crushing Strength
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
0.04
0.02
0
Adjusted Strain
Time Under Load (in Minutes)
1:2:9H
1:2:9
1:6+5
1:3:12
0:1:3H
1:1:6
1:0:3
CITADEL® NO. 65 - SEMI-LOG 2 X 10


1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
CITADEL® NO. 652 - SEMI-LOG 2 X 10
0.8
0.6
0.4
0.2
0
Strain x 10-5
1:0:3
1:2:9H
1:1:6
0:1:3H
1:2:9
1:3:12
GRAPH 17
EARLY CREEP
All Mixes
@ 1/4 Crushing Strength
Time Under Load (in Minutes)



GRAPH 18
EARLY ADJUSTED CREEP
All Mixes
@ 1/4 Crushing Strength
Adjusted Strain
Time Under Load (in Minutes)
0.2
0.1
0
0:1:3H
1:3:12
1:2:9
1:1:6
1:0:3
1:2:9H
1:6+S
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
CITADEL NO. 652
CITADEL NO. 652 - SEMI-LOG 2 X 10


Graph 19
EARLY CREEP
All Mixes
@ 0.70N/mm2 Crushing Strength
0:1:3H
1:3:12
1:2:9
1:2:9H
1:1:6
1:0:3
0
0.2
0.4
0.6
0.8
Strain x 10-5
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
Time Under Load (in Minutes)
CITADEL® NO. 652 - SEMI-LOG 2 X 0

daily (recorded strain with shrinkage subtracted), and another showing the data adjusted by dividing all creep strain readings by the crushing strength of the mix.

The first set of graphs, entitled 'average creep' or 'early creep,' show creep of seven mixes as a function of time under load. Because the mixes had different crushing strengths, the strongest mix was loaded at a stress over 2200% of that on the weakest mix. Tests made under such a wide range of stresses are difficult to interpret, as it greatly increases the measured creep of the stronger mixes relative to the weaker mixes. For an alternative comparison of the behavior of the mixes, the creep data were 'adjusted' by dividing them by the mixes' respective crushing strengths. These adjusted data are the basis of the second set of graphs, entitled 'average adjusted creep' or 'early adjusted creep.' The effect of the stress/strength ratio has been minimized on the 'adjusted' graphs, enabling the data of one mix to be compared to the other mixes. This is less evident in the 'average creep' graphs. The two types of graphs enable creep to be comparatively analyzed two different ways.

For example, Graph 10 shows creep of each mix under a stress of 1/8 its crushing strength, while Graph 11 has been 'adjusted.' The 1:0:3 mix had the highest crushing strength value at 25.15 N/mm^2. From Graph 10, it appears as if this mix also had a large ability to creep; but when the data are adjusted to allow for the effect of its high crushing strength value in Graph 11, the 1:0:3 mix is seen to have the lowest creep values. Correspondingly, the 0:1:3H mix shows low creep values in Graph 10, yet has the highest creeping ability when adjusted to allow for the effect of its low crushing strength in Graph 11. A similar analysis can be made from Graphs 12 & 13, covering creep tests at $\frac{1}{4}$ of each mix's crushing strength.

The 'adjusted creep' graphs allow correlations and conclusions to be made by comparing and contrasting all the mortar mixes tested. The unadjusted creep graphs merely permit the behavior of each mix to be analyzed separately. Comparing the two unadjusted creep graphs provides information on creep as the stress/strength ratio increases. For example, in Graph 10 the 1:0:3 mix reached a creep strain of

0.78×10^{-5} at 21 days, but in Graph 12 at double the stress of Graph 10, the maximum strain was 2.07×10^{-5}. This suggests that the creep strain increased more rapidly than the applied stress as the applied stress approached the ultimate strength of the mortar, a phenomenon first noted by Neville.[15] The strain did not double as the stress did from Graph 10 to 12; it nearly tripled. The same can be said for the other mixes. At 1/8 crushing strength, the 1:3:12 mix had a creep strain of 0.18×10^{-5} at 21 days; at ¼, the strain was 0.50×10^{-5}. At 1/8, the 0:1:3H had a strain of 0.27×10^{-5}; at ¼, the strain was 0.67×10^{-5}. These mixes also nearly tripled.

Graphs 10 & 12 also seem to differ from test conclusions made by Neville in his 1959 testing program on mortars of cement and sand only.[16] He stated that the same creep could be expected in mortars made with different cements, and consequently of different strength, if they were loaded to the same proportion of their strength.[17] Graphs 10 & 12 show that creep was not the same, despite all mixes having been loaded to the same proportion of strength. It should be noted that in this testing program, mortars had mixes of varying proportions while those in Neville's program had constant proportions. However, two mixes under study here had the same proportions, the 1:2:9 and the 1:2:9H mixes. They were loaded to the same proportionate strength, and yet the 1:2:9 and the 1:2:9H creep lines are not near each other. Their creep was not the same.

Graph 14 represents the third creep test on all mixes.[18] All cylinders had aged 77 days or more. All mixes were uniformly loaded at a fixed 0.70 N/mm^2; in this test the crushing strength was not considered. As in Graphs 11 & 13, the mixes with lower crushing strength values and higher lime content, such as the 0:1:3H, crept more than the stronger mixes with low lime content (e.g. 1:0:3).

Graphs 10 - 13 also permit evaluation to be made concerning almost similar mixes. The synthetic mix, 1:6+S, according to product specifications, should be similar to a 1:1:6 mix in all respects. All four graphs show this to be true; the lines for the 1:1:6 and the 1:6+S mixes are closely parallel and in the case of Graph 11, nearly coincide.

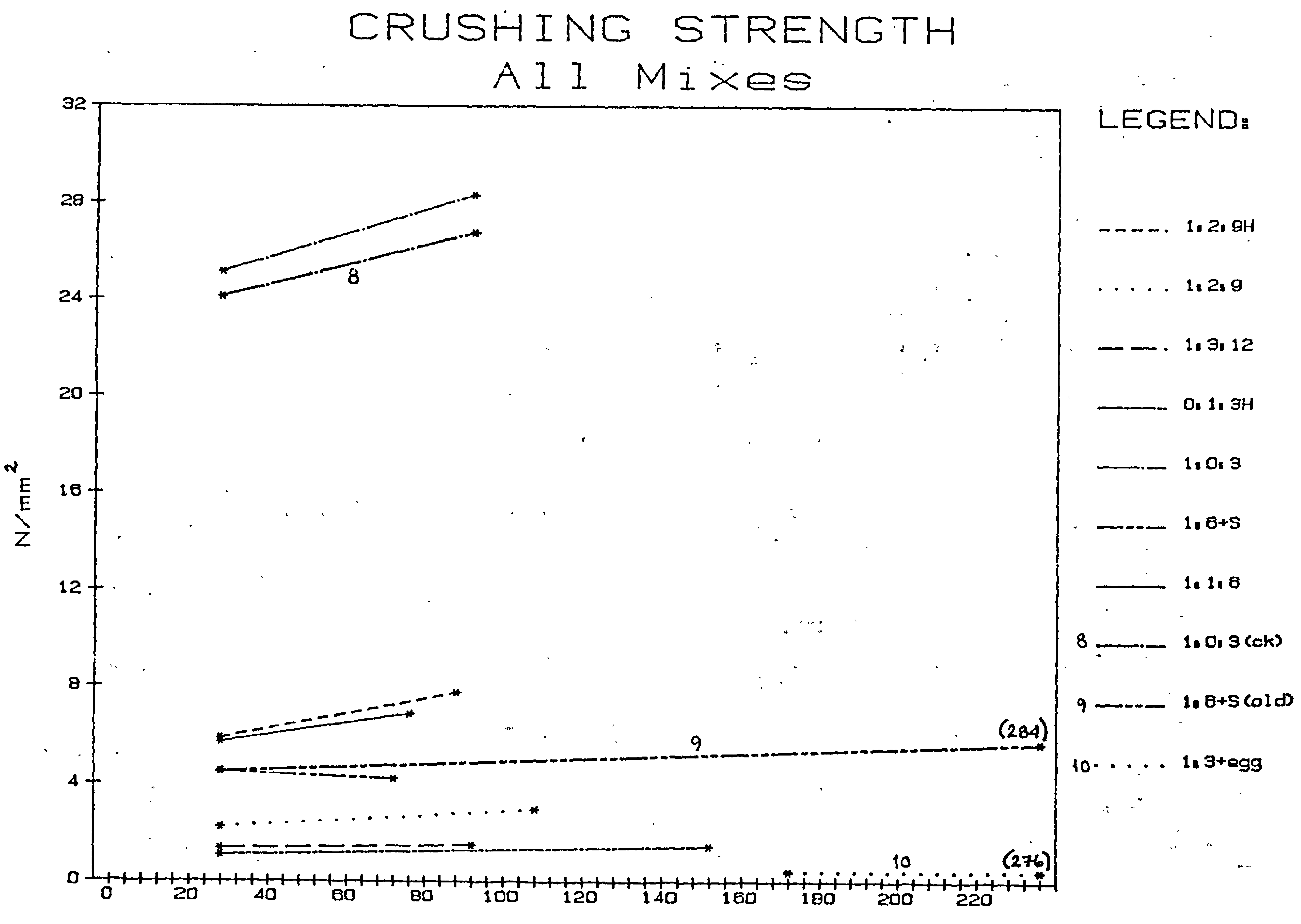
Only creep has been compared; such other effects as weathering ability were not tested.

Initially when mortar mixes were being selected for testing, the 1:2:9H mix was included as it was thought that by testing it against the 1:2:9 mix and the 1:0:3 mix, comparisons could also be made between these mixes and a better understanding of the qualities of hydraulic lime could be gained. Graphs 10 - 14 reveal contrast between the three mixes. The 1:2:9H had a 80% lower crushing strength at 28 days than the 1:0:3 mix: 5.89 N/mm^2 vs. 25.15 N/mm^2. Graphs 10 & 12 show it to have had the highest or nearly the highest creep, while the 1:0:3 mix was second highest most of the time, whereas in the adjusted Graphs 11 and 13, & in Graph 14 the 1:0:3 mix had the lowest creep values, the 1:2:9H mix had the third or fourth highest creep of the seven mixes.

Contrasted to the 1:2:9 mix, the hydraulic 1:2:9H proved to be higher in crushing strength, but had lower or equal creep. The former crushed at 2.21 N/mm^2, the latter at 5.89 N/mm^2. Graph 11 shows the 1:2:9H mix as having a slightly lower adjusted creep, while in Graphs 13 and 14 the creep for both these mixes is nearly identical. One conclusion drawn from these observations is that a hydraulic lime mix appeared to have a greater strength, but a similar creep ability to a hydrated lime mix. In other words, when hydraulic lime was used in lieu of hydrated lime, creep was not sacrificed for the greater strength the hydraulic lime produced in its mix.

Crushing strength and lime content are related by examining Graph 20, which shows crushing strength as a function of age. Graphs 14 & 20 together show that creep had an inverse relationship to the crushing strength. Neville drew this conclusion, but warned that this relation may not be of help in predicting long-term creep from short-term creep data.[19] With the exception of the hydraulic lime mix, each mix with low creep in Graph 14 shows a high crushing strength value in Graph 20, and vice versa. The 1:2:9H mix containing hydraulic lime was the only mix that did not sacrifice one property for the other. As noted above, it had relatively high strength and also high creep.

Graphs 10 - 14 bear out one final point originally noted by Neville: age reduces creep in compression.[20] Although the stress


CRUSHING STRENGTH
All Mixes
LEGEND:
1:2:9H
1:2:9
1:3:12
0:1:3H
1:0:3
1:6+S
1:1:6
8 1:0:3(ck)
9 1:6+S(old)
10 1:3+egg
N/mm²
AGE (IN DAYS)
0
4
8
12
16
20
24
28
32
0
20
40
60
80
100
120
140
160
180
200
220
8
9
10
(284)
(276)

GRAPH 20

on the various cylinders changed from test to test, this point can still be considered by examining Graphs 10 & 14, which have identical y-axis scales to allow for comparisons to be easily made between the two sets of data. In Graph 10, the 1:1:6 mix was loaded, at 28 days of age, at 0.72 N/mm^2, 1/8th its crushing strength. In Graph 14, the same mix was loaded, at 77 days of age, at the fixed 0.70 N/mm^2. As the difference in compressive stress is negligible, creep comparison can be made between the two graphs. Creep has distinctly declined as the age at loading increased. In fact, when loaded at 77 days, creep was reduced by approximately 66%. However, strength was also increasing with age. Between 28 and 77 days of age, the 1:1:6 mix gained approximately 20% in strength (reference Table 22).

This same fact can be noted for the 1:2:9H mix. For the 1/8 crushing strength test, it was loaded at 0.74 N/mm^2. Again, this figure is relatively close to the 0.70 N/mm^2 value for the third test. Examining Graphs 11 & 14, the creep was reduced by approximately 80%, while strength increased by 31%.

The above two examples show that creep was much less in mortars approximately three months old, and suggest that the capacity to creep would continue to diminish with age. Table 22 lists each mix's compressive strength and weight figures at 28 days old and at the day of the third test. A percentage of gain or loss was calculated for each property. The 66% and 80% figures of apparent creep reduction mentioned above cannot be attributed solely, per the graphs, to increasing age. Age may reduce creep in compression, but to what extent is undeterminable from this testing program. Neville stated that relative gain of strength is not a factor in creep, but absolute gain in strength does modify slightly the creep-time curve.[21] Strength gain and moisture loss are important and need to be studied further to determine what percentage of the above 66% and 80% are attributed to them.

Graphs 15 - 19 show early creep, within the first 100 minutes, on a logarithmic scale. Graph 15 corresponds to Graph 10, 16 to 11, 17 to 12, 18 to 13, and 19 to 14, the difference lying in the period of time during which creep was examined. During the first 100 minutes, creep increased at such a high rate that by examining Graphs 10 - 14 a near

Mix	Strength in N/mm^2			Weight in gms		
	@ 28 days	@ 77+ days	% Gained	@ 28 days	@ 77+ days	% Lost
1:2:9H	5.89	7.75	31.58	1000.51	873.93	14.48
1:2:9	2.21	2.95	33.48	971.76	835.10	16.36
1:3:12	1.34	1.49	11.19	976.32	837.62	16.56
0:1:3H	1.07	1.46	36.45	989.44	842.96	17.38
1:0:3	25.15	28.33	12.64	1029.81	944.27	9.06
1:6+S	4.50	4.20	(6.67)*	996.40	883.35	12.80
1:1:6	5.73	6.88	20.07	986.08	857.38	15.36

Table 22: Strength Gain and Weight Loss Over Time
This table shows how much the various mixes gained strength and lost weight (or dried) during the time between testing at 28 days and 77+ days. Refer to Table 21 for the exact age of each mix listed in "77+ days" column.

*The reason for this decrease is not clear. It may be related to the use of the synthetic product, Rendaplas.

vertical line is noted. This behavior makes non-linear relationships difficult to visualize without the use of logarithmic paper. The resulting straight lines enable an equation to be created to define creep in various mortars, and allow an estimate of the magnitude ot creep at later ages to be made. This idea was based on an earlier investigation made by Neville. He found that the small variation between mixes in the rate of creep after 21 days under load was shown by the fact that from that time onward the graphs of creep versus logarithm of time under load plot as straight lines of nearly the same slope for mortars made with different cements.[22] However, Graphs 15 - 19 of early creep do vary enough between the first and 100th minute to allow an investigation to be attempted and an estimate made of the magnitude of creep at later ages.

The slope of all lines was calculated using Graphs 16, 18, and 19.[23] The formula:

$$\text{slope, } m = \frac{y_{100} - y_1}{x_{100} - x_1}$$

was used to determine the slope for each mix. The subscripts, 100 and 1, refer to the minimum and maximum points on the line, namely 100 minutes and 1 minute. As an example, the order for the adjusted strain data at 1/4 crushing strength was as follows:

1:0:3	1.25×10^{-4}
1:1:6	2.65×10^{-4}
1:6+S	3.44×10^{-4}
1:2:9	3.71×10^{-4}
1:2:9H	3.96×10^{-4}
1:3:12	6.50×10^{-4}
0:1:3H	9.03×10^{-4}

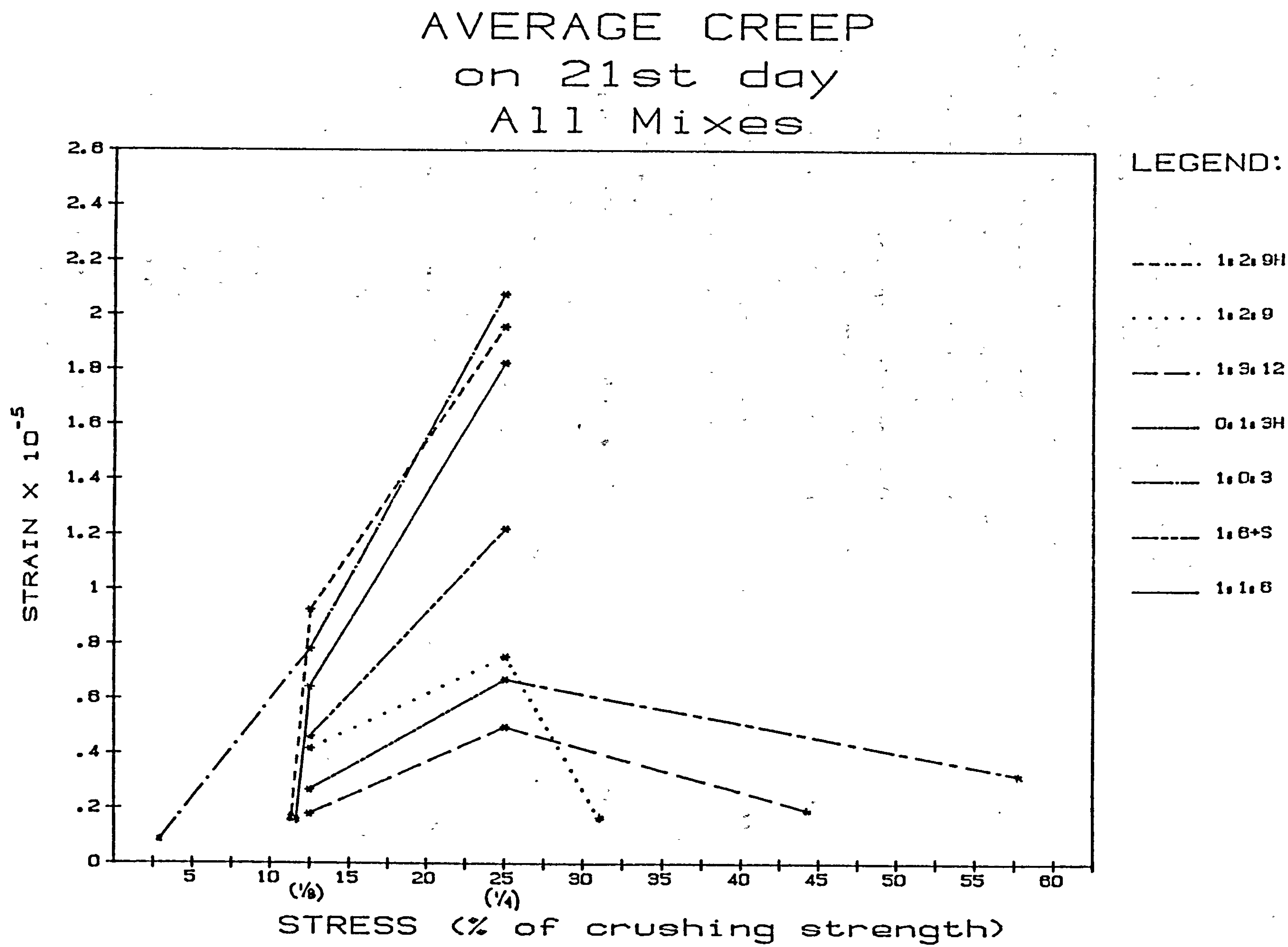
As slope measures the rate of something, in this case creep, this analysis suggests that the higher the slope, the higher the creep rate. The order also shows that the content of lime per mix increased with the rate of the slope. In other words, the rate of early creep (within the first 100 minutes) increased with the lime content of the mixes.

For estimating creep at later ages (still using an adjusted 1/4 crushing strength load as an example), the slope figures suggest that creep in a lime-rich mix such as a 1:3:12 will be approximately five times greater than a 1:0:3 mix. Or, a 1:2:9 mix will creep approximately the same as a 1:2:9H mix. By re-examining Graphs 12 & 13, these estimations are not precise, but do permit some predictions on the future creep of various mixes to be made. Using Graph 13, for example, and looking at creep on the 21st day, the 1:2:9 and 1:2:9H mixes have a similar strain figure: 1.35×10^{-5} vs. 1.30×10^{-5}. The 1:3:12 mix has a strain about five times higher than the 1:0:3: 1.45×10^{-5} vs. 0.30×10^{-5}.

The accumulated data also yielded graphs of the total creep up to 21 days, and elastic strain and recovery. In all creep tests, the cylinders were loaded for a 21-day period. The creep at 21 days was plotted on Graph 21. The compressive stress of 0.70 N/mm^2 in the third test on each mix was expressed as a percentage of the mix's crushing strength. The 21st day under stress for the first two tests occurred when the cylinders were 49 days old, having been loaded at 28 days of age. The 21st day for the third test varied according to the age of the cylinders; the different mixes had different ages at the time of loading due to scheduling conflicts. As previously stated, though, the cylinders were a minimum of 77 days and a maximum of 153 days old when loaded for the last testing period. So, the 21st day under load varied from 98 to 174 days of age of the cylinders.

In Graph 21, the plotted points relating to the third test are those points not in line with the x-axis or stress coordinates marked 1/8 or ¼. They have been connected to the points from the first two tests, but they belong to samples of different age from the samples in the first two tests.

Measurements of creep at similar stresses but different ages were compared. For example, the 1:2:9H mix had similar stress values for the 1/8 crushing strength test and the fixed 0.70 N/mm^2 test, yet the strain values differed by about 0.8×10^{-5}. The lower value of approximately 0.2×10^{-5} corresponded to the third test loaded at


AVERAGE CREEP
on 21st day
All Mixes
LEGEND:
1:2:9H
1:2:9
1:3:12
0:1:3H
1:0:3
1:6+S
1:1:6
STRAIN X 10^-5
2.8
2.4
2.2
2
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
5
10
(1/8)
15
20
25
(1/4)
30
35
40
45
50
55
60
STRESS (% of crushing strength)

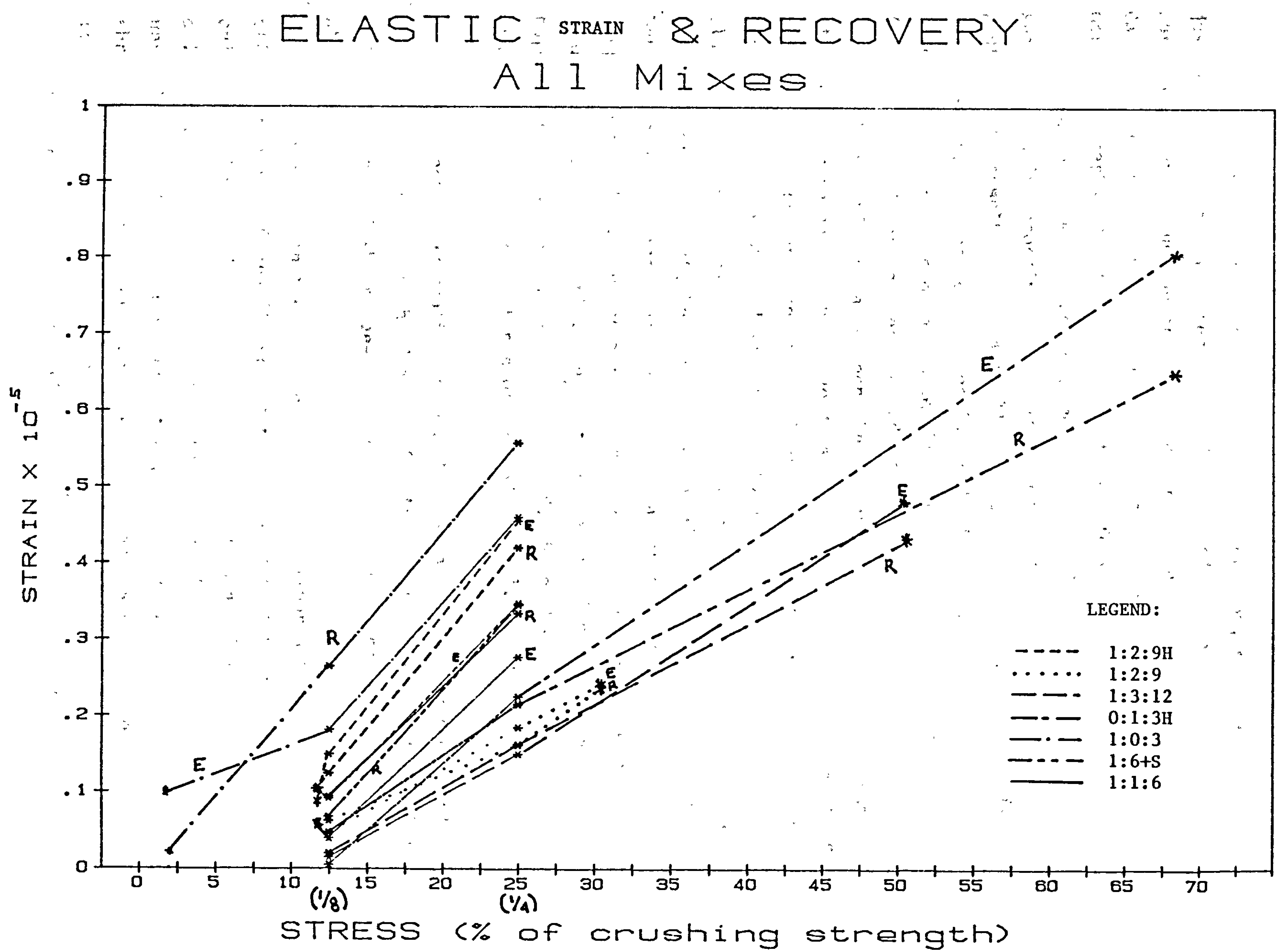
GRAPH 21

age 88 days, while the strain value of approximately 1.0 x 10^{-5} was for the 1/8 crushing strength test at age 28 days. This indicated that at approximately the same stress, the strain value decreased with drying or with age. In other words, creep decreased with age at loading, even under the same stress and same proportion of crushing strength. The 1:1:6 mix provided a parallel example. The 1:2:9H an the 1:1:6 mixes, the second and third strongest mix, were among the stronger of the seven mixes tested. Here, 'stronger' was defined as those mixes having high crushing strengths.

The weaker mixes showed the same effect of age on creep. For example, mix 1:3:12 had approximately the same strain of 0.2 x 10^{-5} for a stress of 1/8 of the crushing strength at age 49 (28 control + 21 test days) as for a stress of 45% of the crushing strength at age 112 (91 control + 21 test days). Despite an additional 63 days of age, and a loading weight of three times that of the earlier 1/8 crushing strength test, this mix had the same total creep. The 0:1:3H mix showed similar effects.

Graph 21 also shows that when two cylinders of the same mix are loaded at different stresses, but concurrently, then creep increased as the stress increased. However with age, independent of stress, creep diminished. The diminishing moisture content of the cylinders is a possible reason. Referring back to Table 22, the weights of the different mixes can be examined. In all cases, the samples lost weight (dried) during the time between testing at 28 days and 77+ days.

Graph 22 records the elastic strain and recovery of each mix at one minute after the load was placed and removed respectively. Based on the recorded values taken with the Demec gauge, and relative to their crushing strength, the values for elastic strain and recovery were highest in the richer mixes. There appears to be no pattern, however, as to whether the stronger or weaker mixes had more complete recoveries. In fact in several cases, the recovery value was higher than the elastic strain measured, suggesting that these mixes were more elastic than the others. The lack of a pattern might arise from the arbitrary choice ot one minute to define elastic strain.


ELASTIC STRAIN & RECOVERY
All Mixes
STRAIN X 10^{-5}
STRESS (% of crushing strength)
(1/8)
(1/4)
LEGEND:
1:2:9H
1:2:9
1:3:12
0:1:3H
1:0:3
1:6+S
1:1:6

GRAPH 22

In the study of mortars and building deformation, shrinkage plays just as vital a role as creep. Both Neville and Lenczner have mentioned shrinkage when discussing creep in their published papers. However to date, no published data has been found specifically on shrinkage in mortars. Graphs 23 and 23.5 provide this information.

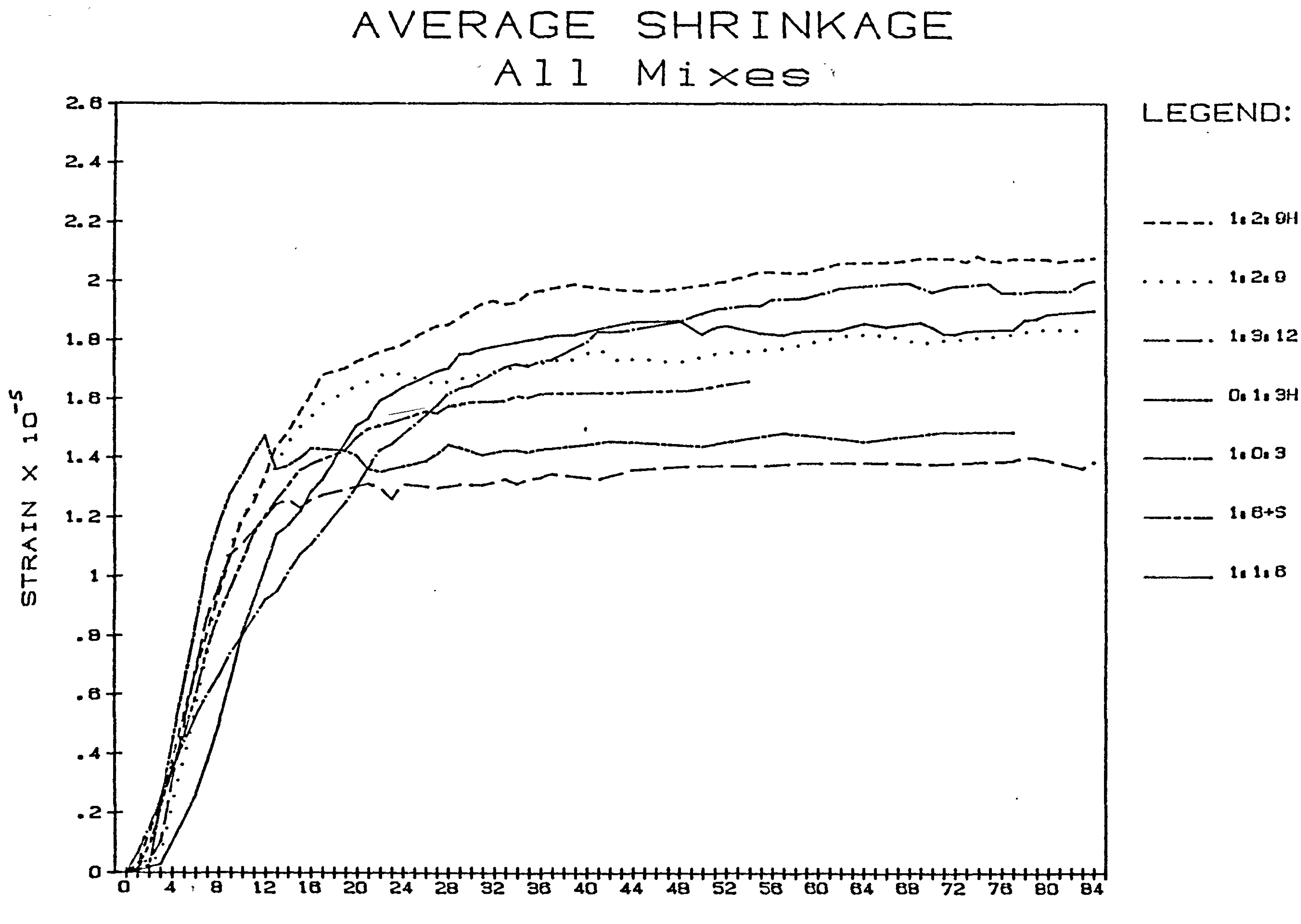
Throughout the testing program, each mix had a set of control samples. Daily recordings of deformation were taken, averaged, and plotted, the result being Graphs 23 and 23.5. During the first 21 days out of water, the control samples for each mix shrank. During the next 23 days, the shrinkage of all mixes began to level out, so that by Day 45 shrinkage had more or less ceased except for minor fluctuations.

Distinct differences between the weaker and stronger mixes became visible by graphing the shrinkage data. The weaker or lime-rich mortars such as the 1:3:12 and the 0:1:3H shrank more within the first 10 days, but leveled out or stopped shrinking before the stronger mixes. They also shrank less overall. The stronger or cement-rich mortars, such as the 1:0:3 or the 1:1:6, had lower rates of shrinkage in the beginning, but continued to shrink for several weeks after the weaker mixes had stopped altogether. Furthermore, they shrank more overall than the weaker mixes. For example, the 1:0:3 mix was still shrinking with an approximate strain of 1.6×10^{-5} on Day 28, while the 0:1:3H mix had begun leveling out at a strain of approximately 1.4×10^{-5} around Day 16.

The effect of hydraulic lime can be examined by noting the 1:2:9 and 1:2:9H curves on Graph 23 and 23.5 which merely show that the 1:2:9H had higher overall shrinkage--in fact, the highest observed shrinkage of all mixes.

Moisture loss in the cylinders is another important factor affecting creep. Graph 24 depicts the daily loss of weight of all cylinders. By Day 25, weight loss had ceased in all but the 1:0:3 cylinders. The 1:0:3 mix continued to lose weight another 37 days, until Day 62. With this one exception, it is interesting to note that shrinkage in the cylinders continued for almost twice the amount of time it took the cylinders to cease losing weight by drying.

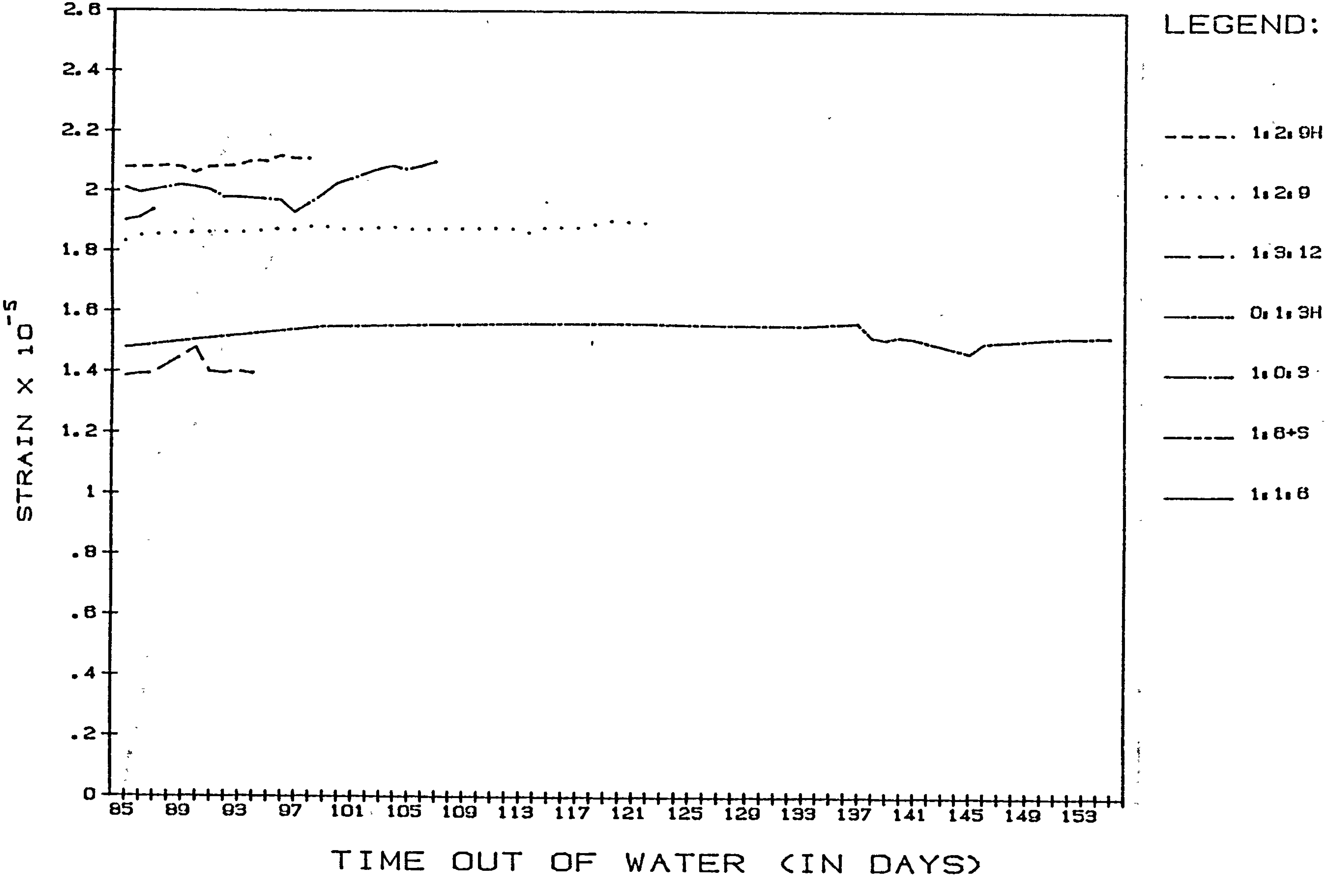
By briefly comparing the shrinkage and weight loss data with those



AVERAGE SHRINKAGE
All Mixes
STRAIN X 10^-5
2.8
2.4
2.2
2
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
0
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84
TIME OUT OF WATER (IN DAYS)
LEGEND:
1:2:9H
1:2:9
1:3:12
0:1:3H
1:0:3
1:6+S
1:1:6

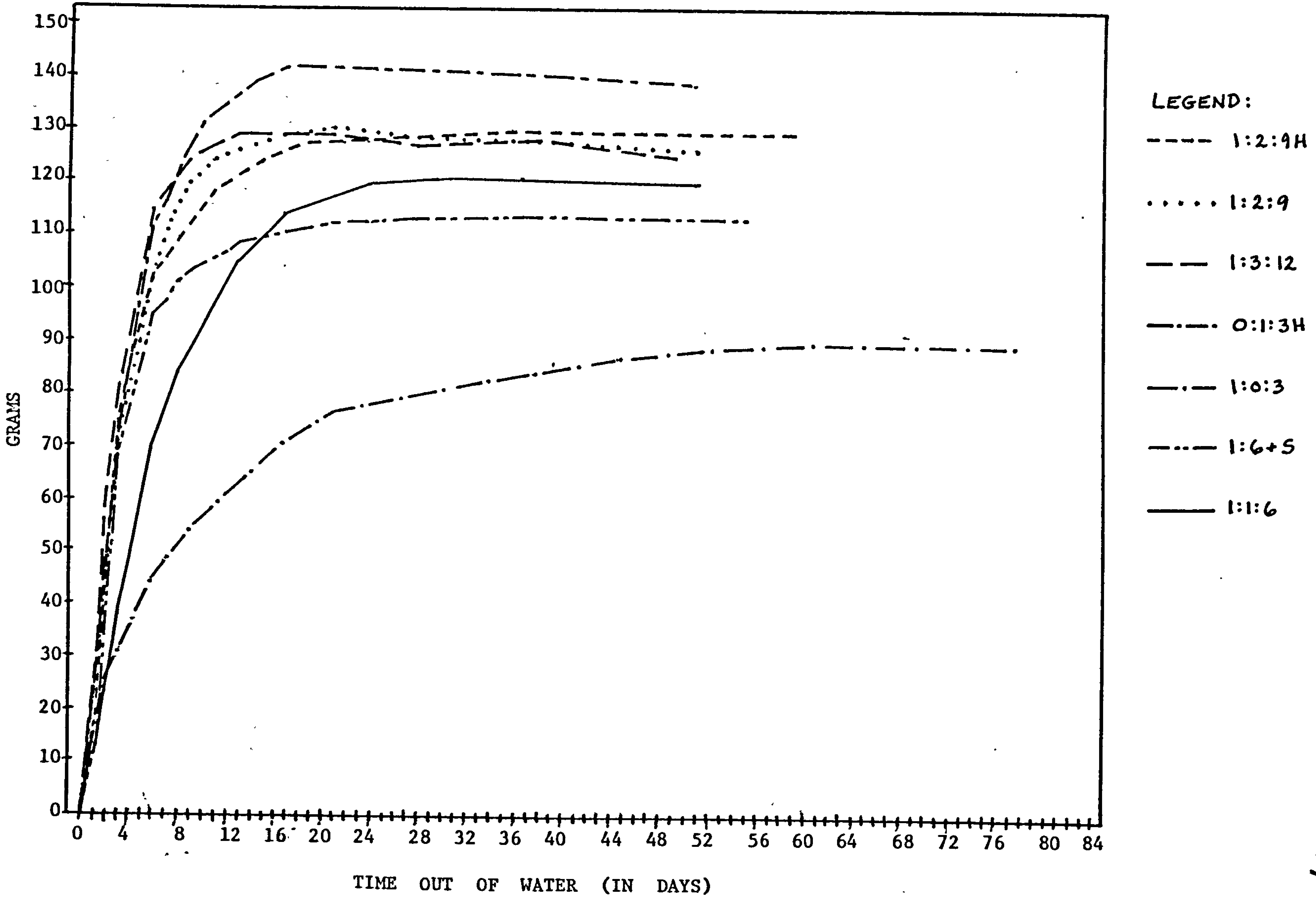
GRAPH 23

AVERAGE SHRINKAGE
(continued)



GRAPH 23.5

AVERAGE WEIGHT LOSS
All Mixes



GRAPH 24

for creep, an interesting correlation is noted. Whereas creep was lowest in the mixes with small amounts of lime, such as the 1:0:3 and 1:1:6 mixes in Graphs 11, 13, & 14, these mixes proved to be among the last to cease shrinking and losing weight. This substantiated the hypothesis that creep, shrinkage, and weight loss are related to the quantity of lime in a mortar mix. The 1:2:9H mix was the exception. It crept considerably more than the 1:1:6, 1:6+S, and 1:0:3 mixes (see Graphs 11 & 13), and yet shrank the most and was the last to cease shrinking. This was an anomaly for hydraulic lime.

The effect Portland cement has on a mix with hydraulic lime needs to be examined. However, the program did not test enough mixes containing hydraulic lime to sufficiently analyze the different behaviors of a hydraulic mix with and without cement. By examining all the graphs for mixes 0:1:3H and 1:2:9H, general conclusions can be made. The 1:2:9H had a higher overall crushing strength (reference Table 22), but the 0:1:3H had a higher percentage of gained strength after 28 days. The 1:2:9H strank more than the 0:1:3H: the former leveled off at an approximate strain of 2.0×10^{-5} while the latter leveled off at approximately 1.4×10^{-5}. The 0:1:3H, on the other hand, had slightly higher weight loss, approximately 10 grams more, and had considerably higher creep strain values on all three tests.

Conclusions

The laboratory procedure allowed precise data to be obtained on creep and shrinkage. The resulting information was graphically presented and analyzed. This data showed that lime-rich mortars have a greater tolerance of structural movements, and substantiated the initial hypothesis that the lime-rich mixes creep more and shrink less.

There are fourteen main conclusions to be drawn from the graphs:

(1) Creep and shrinkage are related to the proportion of lime in a mortar mix.

(2) Creep increased as the proportion of lime in a mix increased.

(3) Creep increased as the crushing strength decreased.

(4) Early creep, within the first 100 minutes, was higher in lime-rich mixes.

(5) The total creep strain increased as the applied load approached the utimate strength of the mortar.

(6) The slopes of the lines for early creep allowed an estimate of the magnitude of creep at later ages to be made.

(7) If two cylinders of the same mix were loaded at different stresses, but concurrently, creep increased as the stress increased.

(8) With increasing age at loading, independent of stress, creep diminished.

(9) The values for elastic strain and recovery were highest in the lime-rich mixes.

(10) All shrinkage more or less ceased after 45 days.

(11) Weight loss ceased after 25 days, except for the 1:0:3 mix which ceased after 62 days.

(12) The weaker or lime-rich mortars shrank more, within the first 10 days, but then leveled out and stopped shrinking. They also shrank less overall than cement-rich mixes. The stronger or cement-rich mortars shrank less in the beginning, but continued to shrink for several weeks after the weaker mixes had stopped altogether. They shrank more overall than the weaker mixes.

(13) Hydraulic lime mortars with cement had relatively high strength and high creep. They crept more than the cement-rich mixes, and yet shrank the most and were the last to cease shrinking. Hydraulic lime mortars without cement, however, had low strength, but extremely high creep. They also had a low shrinkage which ceased first of all seven mixes.

(14) A synthetic mortar of a 1:6+S mix, made with a specific commercial product, crept and shrank similar to a normal 1:1:6 mortar.

These conclusions, when combined with knowledge gained outside of the laboratory and the case studies examined, will provide further understanding of mortars, their specification, and their application in the restoration of old structures.

References and Notes

1. See Appendix 3 for a listing of equipment and material sources.

2. Wykeham Farrance Engineering Ltd., Weston Road, Trading Estate, Slough, Berks. SL1 4HW England.

3. David Lenczner, "Creep in Brickwork, Proceedings of the 2nd International Conference on Brick Masonry, SIBMAC, April 1970, p. 45.

4. Steel moulds were available from Wykeham Farrance, but not in the required size.

5. See Appendix 3 for a full description of the pipe and its source.

6. See Appendix 3 for a description and source list on the products used.

7. Due to scheduling and time factors, it was impossible to age all mortar samples to a fixed date after they reached the age of 60 days. Data showed that shrinkage, on a whole, had stopped by two months so it was not vital that the second aging period be precise. In the case of the cement test, the early cube samples were aged to 91 days; the later samples, to 63 days.

8. If the cube does not form an "hourglass" after crushing, it was not centered accurately to allow the compressive force to be evenly distributed over its surfaces.

9. This consistency test followed the format established by British Standard #4551: 1980, 17.

10. J.J. Brooks and A.M. Neville, "A comparison of creep, elasticity and strength of concrete in tension and in compression," Magazine of Concrete Research, v.29, n.100, Sept. 1977, p. 133; Lenczner, "Creep in Brickwork," 45.

11. Sandor Popovics, Concrete-Making Materials (London: Hemisphere Publishing Corp., 1979), p. 80.

12. The oldest testing took place with mortar aged 179 days (an aging period of 153 days, 21 days of testing, and 5 - 6 days of recovery).

13. During the preliminary testing, the 1:3:12 mortar cubes crushed at 1.89N/mm^2 at 28 days. It was decided to take about 1/3 of 1.89 or 0.70 N/mm^2 as the fixed weight load for the second set of

tests. (This load approximates that of brickwork 35 meters high). However, the 1:3:12 and 0:1:3H mixes were loaded at lower figures because 0.70 N/mm^2 was judged to be unreasonably high -- about half the crushing strengths of these mortars. A slightly lower fraction (2/5) of the crushing strengths was selected which would produce load figures close to the 0.70 N/mm^2. Two-fifths of the 1:3:12's crushing strength of 1.49 N/mm^2 was 0.59 N/mm^2, and 2/5ths of the 0:1:3's crushing strength of 1.46 N/mm^2 was 0.58 N/mm^2.

14. As is expected, Graphs 10 & 12, and 11 & 13 correspond to each other respectively. In other words, the order the mixes take per their creep values are the same in Graph 10 as in Graph 12, and in Graph 11 as in Graph 13; the only difference being that the values are higher at ¼ crushing strength than at 1/8.

15. A.M. Neville, "Role of Cement in the Creep of Mortar," Proceedings of the American Concrete Institute, v.55, n.3, Mar. 1959, p. 982.

16. Neville, "Role of Cement," 972.

17. Neville, "Role of Cement."

18. The synthetic mix, 1:6+S, was not tested due to the lack of time.

19. Neville, "Role of Cement," 977.

20. Brooks and Neville, "A comparison of creep," 140.

21. Neville, "Role of Cement," 975.

22. Neville, 976.

23. Graphs 16 & 18 are adjusted creep, and Graph 19 is creep at the fixed load of 0.70 N/mm^2. The adjusted graphs were used instead of the early creep graphs as the resulting slope data permitted comparisons to be made between all the mixes by minimizing the effect of the stress/strength ratio.

Chapter 7: Summary, Application, and Further Research

Introduction

This thesis has primarily dealt with the fundamentals of creep and shrinkage by examining case studies and conducting laboratory tests. Some of the findings of Lenczner and Neville have been confirmed, and considerable additional information concerning creep and shrinkage in mortars (exclusive of masonry) has been obtained. Previous knowledge of creep and shrinkage has been limited; most scientific creep studies have sought to discover properties of modern masonry materials as applicable to new masonry construction. Mortar mixes alone have not previously been tested for creep and shrinkage in a laboratory. Organizations such as the ASTM in the United States and the BRE in the United Kingdom have studied properties of mortars of various mixes, but not as applicable to the restoration of old buildings.

The knowledge gained by testing shrinkage and creep in the laboratory not only helps explain behavior observed in the case studies, and explains McKee and Feilden's rule in scientific terms, but allows tentative predictions to be made on the future behavior of certain mortars in the real, built environment, and provides new data from which future research can stem.

Limitations

As with any investigation, time was a limiting factor. Furthermore, once this study was underway the scope changed and areas requiring further study developed. This project covered three years of which one and one half were devoted to laboratory experiments on creep and shrinkage in mortars. A trial period was necessary to iron out kinks in the procedure and to produce a streamlined schedule for the actual testing period. It was during the months of preliminary laboratory work that the humidity and temperature were controlled and stabilized.

Eight mortar mixes were originally selected for testing. Seven were retained and tested in the final program. A mix of 0:1:3+egg whites was eliminated because it would not harden sufficiently to permit removal from the cylinder and cube moulds. It was originally intended to test a synthetic and an organic mortar mix to compare their results to the standard mixes such as 1:1:6, 1:2:9, and 1:3:12. The egg white mix was made according to recipes mentioned by Vitruvius and Pliny (see Chapter 3).

Historical Chapters

Chapters 1 - 3 provided a historical synopsis of the efforts to improve mortars, focusing primarily on the binder ingredients, since the time of Vitruvius and Pliny. Men considered the quality of mortars to depend on the additives employed and the chemistry of the binders. Initially they based the quality on selecting naturally occurring ingredients that imparted the desired properties. Portland cement had a profound effect on the building trades as the new material gained universal acceptance. Technological advancements, in time, permitted further innovations, notably synthesized chemical additives.

These chapters discussed the developing science of mortar, providing a basis for present day scientific knowledge. The material provided a basic understanding of mortars, particularly those made of the three traditional ingredients. This data provided the basis for new research into how simple mortars behave.

Case Studies

The case studies were employed to present data on mortars in the built environment. Observing repairs as they aged raised questions which, it was hoped, would be answered by the laboratory test results.

In the first group of cases, lime/cement >= 4, the issue of shrinkage arose due to the excessive shrinkage of the 0:1:3H originally used in the restoration of Thirlestane Castle. The second group, 2 <= lime/cement < 4, showed the need for further study comparing the use of hydrated and hydraulic lime in a mix. The third set of cases, $\frac{1}{2}$ < lime/cement < 2, served as checks and balances against mixes recommended by governmental agencies, and invited comparisons. In the last group, lime/cement <= $\frac{1}{2}$, the mortars had no lime or low-lime contents, and raised questions about plasticity and its aid in preventing deterioration.

The issue of shrinkage at Thirlestane Castle showed the need for further study. As stated in Chapter 4, the keep was originally repointed using a 0:1:3H mortar. Excessive shrinkage occurred, forcing the architect to rake the 0:1:3H out and start again with a 1:2:9H mortar. The only similarity between the mixes was the use of hydraulic lime.

The conclusions listed at the end of Chapter 6 characterize a 0:1:3H mix as one with extremely high creep, low strength, low overall shrinkage, and low moisture loss. These results, obviously, differed from those initially obtained at Thirlestane; shrinkage should have been low. However in the application of 0:1:3H mortar at Edinburgh and Craigmillar Castles, no problems have been noted. There is no immediate explanation for these contradictory observations. Possible reasons for the Thirlestane problem include improper preparation of the mortar by the masons, or insufficient washing of the sand to remove the sea salt (if it was beach sand). The impact salt might have on a mortar is important and thus, requires further study.

Hydraulic vs. hydrated lime was another issue raised by the case studies. Scientific comparisons between mortars made with the two limes have not previously been made. As discussed in Chapter 6, the test results showed that when hydraulic lime (1:2:9H) is used in lieu of hydrated lime (1:2:9), creep is not sacrificed for the greater strength the hydraulic lime produces in a mix. The shrinkage data also showed that the 1:2:9H mortar had the highest overall shrinkage of all the mortars tested. Again this produced unanswered questions in reference to Thirlestane Castle. According to the test data, the 1:2:9H should have shrunk more and thus, possibly created problems at the castle. Observations, however, show that there are minor hairline cracks, nothing more.

The cases restored with mortars recommended by governmental agencies have, on a whole, shown no signs of deterioration, thus verifying the governmental advice. Hairline cracks have been observed in the 1:1:6 mortar at the Public Theatre, but they have been attributed to such external factors as subway vibrations.

Lastly in the fourth group of cases, the issues of plasticity and deterioration were raised. Several case studies, namely Chesterwood and Old North Church, involved cement-rich mortars containing no lime. The effects of a pure cement mortar were ultimately shown: Chesterwood was continually under repair during French's lifetime, and Old North Church has damaged bricks and broken arrises.

Furthermore, these conclusions and the problems presented in the above two case studies reiterate McKee and Feilden's rule: a mortar should never be stronger than the bricks to which it is jointed. The weaker the mortar (consistent with load-carrying and durability requirements), the more tolerant of movements the wall will be.

Creep and Creep Testing

Chapters 5 and 6 dealt with various aspects of wall behavior, centering on creep and shrinkage in mortars. Chapter 5 served as a forerunner to Chapter 6 by defining scientific terms relevant to wall movement, by discussing the stresses walls undergo, and by listing types of strain (e.g. instantaneous, plastic, etc.), thus providing the lay reader with a general understanding of wall behavior.

The chapter continued by emphasizing the importance of mortar in walls. Several British organizations were quoted on the qualities a mortar should have, and they stressed that foremost a mortar must 'fit its environment.' The mortar used should contain no more cement than is necessary to give adequate strength in brickwork. An unnecessarily strong mortar concentrates the effects of any differential movement in fewer and wider cracks; a weaker mortar accommodates smaller movements and any cracking would be distributed as hair cracks in the joints. The British Building Research Establishment created charts on mortar selection based on location and desired properties.

Creep was selected as the main aspect of wall movement to be studied (see Chapter 6), so previously published work on the subject was examined. Neville and Lenczner are the principal investigators in this field, but their work dealt with structures built of both mortar and brick. Their laboratory procedures were detailed in this chapter, from control of the environment and curing of sample cylinders to the creep machines and the test results. Their findings provided a background of relevant knowledge on which the present program of mortar testing was designed, and allowed test data obtained under similar conditions to be compared.

In Chapter 6, the information provided in Chapter 5 was applied to a testing program dealing strictly with mortars. Seven mortar mixes were tested, using general procedures established by Lenczner and Neville, to provide values of strength, creep, and other variables. At 28 days of age, two samples of each mix were loaded in creep machines at 1/8 and 1/4 the crushing strength. At a minimum age of 70 days, one sample of each was loaded at a fixed $0.70 N/mm^2$. Creep under load was measured on a daily basis for 21 days.

All aspects of the program were discussed, from the preparation of the laboratory equipment and materials and the stabilization of the environment to the use of control samples and the different data collected: strength, shrinkage, creep, elastic strain, and weight loss. Extensive tables and graphs as well as text discussed the conclusions. Creep, shrinkage, and weight loss were shown to be related to the quantity of lime in a mortar mix. (The 1:2:9H was the exception.) Creep increased as the proportion of lime in a mix increased, and as creep increased, strength decreased. Also by loading two cylinders of the same mix at different stresses, it was shown that creep increased as the stress inceased.

The synthetic mortar (1:6+S) behaved similarly to an ordinary 1:1:6

mortar, as expected. The hydraulic lime mortar with cement (1:2:9H) had high strength, high creep, and high shrinkage. The hydraulic mortar without cement (0:1:3H) had low strength, but retained high creep, and had the lowest shrinkage values of all mixes tested. The 0:1:3H shrinkage data contradicted the observations of the Thirlestane case study. As previously noted on page 256, the Thirlestane Castle keep showed unacceptably high shrinkage using a 0:1:3H mix.

Lime-rich mixes had higher values for early creep (within the first 100 minutes), and for elastic strain and recovery. These mixes also had higher values of shrinkage during the first 10 days, but did shrink less overall than cement-rich mortars. The conclusions reached from the testing program showed that lime-rich mortars have a greater tolerance of structural movements, and substantiated the initial hypothesis that the lime-rich mixes creep more and shrink less.

Applications

Within a limited scope, predictions of how certain mortars will function with time can be made, and guidelines presented on the proper mortar type and mix proportions for a particular restoration or repair project.

Research has already been completed by the ASTM and the BRE to aid specifiers in selecting the proper mortar. The resulting advice is given in ASTM's Standard C-270: Specifications for Mortar for Unit Masonry, and in BRE's Digest 160: Mortars for Bricklaying (reference Tables 23 - 25).

Standard C-270 breaks all mortars into five groups: M, S, N, O, and K. Digest 160 does similarly, labelling its groups: i, ii, iii, iv, and v. The groups are approximately interchangeable: M = i, S = ii, etc. Except to define the minimum compressive strength expected of each group (Table 24), and to briefly mention admixtures, Standard C-270 provides no other requirements. Digest 160, however, continues. It states the desired properties of a mortar, discusses air-entrained mortars, and provides specific information, in the form of text and

TABLE II.—MORTAR PROPORTIONS BY VOLUME.

Mortar Type*	Parts by Volume of Portland Cement, or Portland Blast-Furnace Slag Cement	Parts by Volume of Masonry Cement	Parts by Volume of Hydrated Lime or Lime Putty	Aggregate, Measured in a Damp, Loose Condition
M	1	1 (type II)	...	Not less than 2 1/4 and not more than 3 times the sum of the volumes of the cements and lime used.
	1	...	1/4	
S	1/2	1 (type II)	...	
	1	...	over 1/4 to 1/2	
N	...	1 (type II)	...	
	1	...	over 1/2 to 1 1/4	
O	...	1 (tyne I or II)	...	
	1	...	over 1 1/4 to 2 1/2	
K	1	...	over 2 1/2 to 4	

Table 23: Mortar Proportions by Volume

Taken from: American Society for Testing and Materials, Specifications for Mortar for Unit Masonry, American National Standard C-270.

Mortar Type	Average Compressive Strength @ 28 days in psi	in N/mm^2
M	2500	17.24
S	1800	12.41
N	750	5.17
O	350	2.41
K	75	0.52

Table 24: Compressive Strength of Cubes for Mortar Types

Taken from: American Society for Testing and Materials, Specifications for Mortar for Unit Masonry, American National Standard C-270.

Table : Mortar mixes (proportions by volume)

	Mortar group	Cement : lime : sand	Masonry-cement : sand	Cement : sand, with plasticiser
Increasing strength but decreasing ability to accommodate movements caused by settlement, shrinkage, etc ↑	i	1 : 0–¼ : 3	—	—
	ii	1 : ½ : 4–4½	1 : 2½–3½	1 : 3–4
	iii	1 : 1 : 5–6	1 : 4–5	1 : 5–6
	iv	1 : 2 : 8–9	1 : 5½–6½	1 : 7–8
	v	1 : 3 : 10–12	1 : 6½–7	1 : 8

Direction of changes in properties:

- ⟵ equivalent strengths within each group ⟶
- increasing frost resistance ⟶
- ⟵ improving bond and resistance to rain penetration

Where a range of sand contents is given, the larger quantity should be used for sand that is well graded and the smaller for coarse or uniformly fine sand.

Because damp sands bulk, the volume of damp sand used may need to be increased. For cement: lime: sand mixes, the error due to bulking is reduced if the mortar is prepared from lime: sand coarse stuff and cement in appropriate proportions; in these mixes 'lime' refers to non-hydraulic or semi-hydraulic lime and the proportions given are for lime putty. If hydrated lime is batched dry, the volume may be increased by up to 50 per cent to get adequate workability.

Table 25: Mortar Mixes

Taken from: Building Research Establishment, "Mortars for bricklaying," Building Research Establishment Digest 160 (London: Her Majesty's Stationery Office, 1973), p. 3.

tables (reference Tables 25 - 26), on the selection of mortars.

Table 25 defines each of the five mortar groups, and at the same time, informs the specifier of their general properties. A 1:1:6 is stronger than a 1:3:12, but less able to accommodate movement; and a 1:6 with plasticiser (similar to the 1:6+S tested in Chapter 6) is better able to resist frost than a 1:1:6, but does not bond as well as the 1:1:6. Table 26 goes one step further in helping the specifier by providing examples of where a mortar type would best be used. Digest 160 states that the guiding principle in using these tables is that the mortar used should contain no more cement than is necessary to give adequate strength in the brickwork, unless there is good reason for choosing a richer mix.[2] An unnecessarily strong mortar concentrates the effects of any differential movement in fewer and wider cracks; a weaker mortar will accommodate small movements and any cracking will be distributed as hair cracks in the joints. The stresses resulting from restraint of any expansion of bricks are reduced if a relatively weak mortar is used.[3]

These documents are by no means the final word on mortar selection. Other digests exist that further aid a specifier. For example, BRE's Digest 61: <u>Strength of brickwork, blockwork and concrete walls</u> provides a table (reference Table 27) that recommends a mortar mix based on the brick strength.

The information quoted from these three documents has, however, been limited to mixes containing Portland cement, hydrated lime, and sand. Mention of plasticisers has been made in the documents, but no examination of hydraulic lime, in lieu of hydrated lime, has been conducted. Such research was undertaken in this thesis due to the growing popularity of hydraulic lime mortars in Great Britain. The findings and conclusions reached in Chapter 6 extend the knowledge currently found in Standard C-270 and Digest 160. The use of hydraulic lime mortars is discussed below.

In selecting a mortar type for specifications, there are certain aspects to consider. The strength of the mortar and its compatibility with the surrounding building units are, perhaps, the most important factors. Climatic and economic conditions are considerations as are the

Table 3. Selection of mortar groups

Type of brick:	Clay		Concrete and calcium silicate	
Early frost hazard[a]	no	yes	no	yes
Internal walls	(v)	(iii) or (iv)[b]	(v)[c]	(iii) or plast(iv)[b]
Inner leaf of cavity walls	(v)	(iii) or (iv)[b]	(v)[c]	(iii) or plast(iv)[b]
Backing to external solid walls	(iv)	(iii) or (iv)[b]	(iv)	(iii) or plast(iv)[b]
External walls; outer leaf of cavity walls:				
—above damp-proof course	(iv)[d]	(iii)[d]	(iv)	(iii)
—below damp-proof course	(iii)[e]	(iii)[b, e]	(iii)[e]	(iii)[e]
Parapet walls; domestic chimneys:				
—rendered	(iii)[f, g]	(iii)[f, g]	(iv)	(iii)
—not rendered	(ii)[h] or (iii)	(i)	(iii)	(iii)
External free-standing walls	(iii)	(iii)[b]	(iii)	(iii)
Sills; copings	(i)	(i)	(ii)	(ii)
Earth-retaining walls (back-filled with free-draining material)	(i)	(i)	(ii)[e]	(ii)[e]

a during construction, before mortar has hardened (say 7 days after laying) or before the wall is completed and protected against the entry of rain at the top

b if the bricks are to be laid wet, *see* 'Cold weather bricklaying'

c if not plastered, use group (iv)

d if to be rendered, use group (iii) mortar made with sulphate-resisting cement

e if sulphates are present in the groundwater, use sulphate-resisting cement

f parapet walls of clay units should not be rendered on both sides; if this is unavoidable, select mortar as though *not* rendered.

g use sulphate-resisting cement

h with 'special' quality bricks, or with bricks that contain appreciable quantities of soluble sulphates.

Table 26: Selection of Mortar Groups

Taken from: Building Research Establishment, "Mortars for bricklaying," <u>Building Research Establishment Digest 160</u> (London: Her Majesty's Stationery Office, 1973), p. 2.

* * * * * * * * * Brick Strength * * * * * * * *			Mortar Mix
	psi	N/mm^2	
Low	1500	10.34	1:2:9
Medium	3000 - 5000	20.69 - 34.48	1:1:6
High (Class B)	7000 - 9000	48.28 - 62.07	1:¼:3
Very high (Class A)	10000 +	68.97	1:0:3

Table 27: Suitable Mortar Mixes for Various Brick Strengths

Taken from: Building Research Station, "Strength of brickwork, blockwork and concrete walls," <u>Building Research Station Digest 61</u> (London: Her Majesty's Stationery Office, 1973), p. 2.

particular use of the new mortar, e.g. shallow or deep repointing, rebedding, or rendering.

Test data in this thesis are in agreement with data in the government publications. For example, using Table 21 on page 223 and Graph 14 on page 229, it was shown that a 1:1:6 mix had a high strength value, yet had low creep values. In reverse, a 1:3:12 mix had a low strength value, but higher creep values. These findings confirmed the data given in Digest 160 (reference Table 25). Examining the strength values alone, confirmation of Digest 61 was made. The 1:1:6 mix crushed at 5.73 N/mm^2; Standard C-270 (Table 24) listed a 1:1:6 as having a strength of 5.17 N/mm^2, having already established a 1:1:6 as a Type N mortar.

While confirming existing data, the present study provides further information to aid the specifier. Table 25 states that as the strength of a mortar increased the ability to accommodate movement decreased. The creep data given in Chapter 6 enables a specifier, within a limited scope, to recognize differences in tolerance for movement of mixes which are similar in strength. For example, Table 25 states that the 1:1:6 mix and the 1:6+S mix should have similar strengths. However referencing Graphs 10 and 12 on pages 225 and 227 respectively, it is noted that the synthetic mix containing the plasticizer crept less than the 1:1:6 mix. Since tolerance for movement is always desirable, 1:1:6 should be preferred in normal circumstances and 1:6+S should be considered only if it meets a particular problem, such as severe exposure to frost.

Another useful argument concerns the 1:2:9 and the 1:2:9H mixes of this thesis. The mix containing hydraulic lime was twice as strong as that containing hydrated lime and yet they shared similar creep values (reference Graphs 11, 13, and 14 on pages 226, 228, and 229 respectively). Thus 1:2:9H can be used in walls with higher loads, without sacrifice of tolerance for movement.

By again examining Table 21 (page 223), it is noted that the 1:2:9H mix has a similar strength as that for the 1:1:6 mix. Now referencing Graphs 10 - 14, it is noted that the 1:2:9H has a slightly higher value of creep. Thus, when seeking good tolerance of movement as well as the strength of a Type (iii) mix, 1:2:9H should be preferred to 1:1:6.

Inveraray Jails and the Ticknor-Campbell House provide another comparison of Type (iii) mixes. Inveraray Jails were repointed with a 1:2:9H mix, the Ticknor-Campbell house in a 1:3 masonry mix:sand which is like a 1:1:6. The latter case study's repair has begun to crack again; the jails, on the other hand, still retain tight joints. These case studies and the test data of this thesis suggest that cracks would not reappear if the Ticknor-Campbell house was repaired once more using a 1:2:9H mix. (This suggested remedy assumes that the strength of a Type (iii) mortar is required and that hydraulic lime is available.)

As has been reiterated throughout this thesis, mortar should never be stronger than the building units to which it adheres. Compatibility between mortar and building unit is essential. Table 27, copied from Digest 61, lists mortars considered 'suitable' for use with various strengths of brick because the use of stronger mortars would not increase the strength of the masonry; and can be used as a guide to mortars whose strength is considerably less than that of the bricks listed (reference Table 24 for mortar strength). In the case of Drayton Hall where the bricks were known to be hand-packed and very soft, a 1:4:8 mix was employed. At Old North Church in Boston, the soft brick walls were repointed with a 1:0:3. According to Table 27, only a very high strength brick justifies the use of this latter mortar. There were no cracks in the mortar at Drayton Hall. The damaged bricks at Old North Church result from the use of mortar which was, by Table 27, highly 'unsuitable.'

Climatic and economic factors are important to a specifier. They are considered in Table 26 and introduced into this research as components of the case studies. For example, Schermerhorn Row experiences severe winters with snow, hot summers, and winds that blow off the East River. These climatic conditions produce a wide range of temperatures and humidities. Settlement is also a factor as the Row sits on in-fill land. A mortar must accommodate these conditions.

The Schermerhorn architect considered repointing and rebedding with a mortar based on an analysis of the original. However, the original mortar employed hydraulic lime, a product not commercially available in the United States and economically infeasible to import. The final mortar selected, a 1:4:8, closely approximated the original, though it contained hydrated lime. As the source of the original sand was no longer available, a color match was achieved by using several different sands imported from Connecticut, New Jersey, and Long Island, rather than employ a pigment. The restored brick walls show no signs of damage. Schermerhorn Row is just one example showing the many factors involved in mortar specification.

The compilation of Tables 23 - 27 enable a specificer to examine a variety of mortar mixes and their properties. By providing case studies subject to different environmental changes, applications of these mixes can be studied and compared, as above, to suggest whether one mix might have been better than another (e.g. Inverarary Jails and Ticknor-Campbell House). A table, similar to Table 26, containing the conclusions of this thesis as well as those found in standards and other similar documents would be enormously useful. However, only mortars were tested; it would be premature to apply those data to parts of a building, as listed in Table 26, such as internal walls, sills, and exterior walls above or below a damp-proof course.

Some useful extension, however, can be made of Table 25, using the seven tested mortars. The product is Table 28. The mortars are defined by strength, creep, and shrinkage based on the testing data and the case studies. The decreasing creep vertically and the increasing creep horizontally to the left confirm an initial hypothesis that mortars with higher creep show greater tolerance to movements in masonry. By also listing the British mortar groups they fall into, the seven mortars could then be applied to Table 26. A specifier now has the mortar selections recommended by standards and other similar documents as well as updated mortar information, culminating in Table 28, to aid in proper mortar selection. No one simple table or flow chart can precisely determine the ideal mortar for a given restoration or repair project.

Increasing strength; decreasing creep ↑

Mortar Group	Mortar Mixes		
i	1:0:3		
iii	1:2:9H	1:1:6	1:6+S
iv	1:2:9		
v	0:1:3H	1:3:12	

← equivalent strengths within each group →

← increasing shrinkage

← increasing creep

Table 28: Mortar Mix Selection Using The Results of This Thesis

Future Research

This thesis opens many possibilities for future research into creep in mortars. The simplest means of extending the research of creep would be to continue testing similar cylinders of mortar in similar creep machines, varying factors that were held constant during the current tests. For example, the effect of the aggregate/binder ratio--kept at a constant value of 3 throughout the completed experiments--could be tested by comparing creep in mortar mixes with an aggregate/binder ratio of 2 or 4. Thermal or moisture cycles could be created in a suitable laboratory to simulate the effects of weather on mortars. Long-term creep over several years could be studied. These suggestions would permit application to the built environment and further expand the specification information given in Tables 23 - 28, particularly the last table. The knowledge gained would add to the existing scientific data on creep.

Another possibility for research could be the laboratory creep testing of a combination of new and old materials, which has not yet been attempted. The easiest scheme is probably the testing of piers built of old (soft) bricks and new mortars.

The next step might be in-situ testing of creep in historic structures. Strain readings of actual walls could be recorded and analyzed, complemented by visual monitoring of cracks and consideration of environmental conditions. Behavior of several mortars could be compared by selecting a uniform-appearing wall and repointing different sections of it with different mortars.

As previously stated, shrinkage is an important issue, but little data have been published to date. The data acquired in this testing program was limited to mortars alone, but additional study could be made on shrinkage in brickwork. By making mortar samples and building a brick wall from the same batches of mortar, shrinkage could be monitored. Calculations could be made to determine how much of wall shrinkage is due to shrinkage in the mortar. This might shed additional light on the study that stated that 60 - 80% of the total deformation of a loaded wall takes place in the mortar bed joints.[4]

These suggestions, examining creep, shrinkage, and other movements in masonry rather than mortars alone, would advance the limited knowledge of creep in conservation. Laboratory data resulting from any study in this area would not only help produce a table such as Table 26 for conservation purposes, but might aid in introducing new governmental standards directed at conservation.

Conclusions

This thesis, for the first time, has presented detailed data on creep and shrinkage in mortars. It was a totally new study of mortars bearing new data, but was based on previous testing undertaken by Lenczner and Neville. The extensive testing program yielded 14 conclusions concerning creep, shrinkage, weight loss, etc. in a laboratory setting. These 14 points are given at the end of Chapter 6.

Salient findings of Lenczner and Neville were considered. Some were confirmed by the new research, particularly the statements: 'age at loading reduces creep in compression,' 'creep is inversely proportional to the crushing strength,' and 'creep strain increases more rapidly than the applied stress as the applied stress approaches the ultimate strength of the mortar.' Other statements either could not be verified or were not supported by the new research: 'the same creep could be expected in mortars made with different cements, and consequently of different strength, if they were loaded to the same proportion of strength' and 'relative gain of strength is not a factor in creep, but absolute gain in strength does modify slightly the creep-time curve' could not be verified under this testing program.

Furthermore in Chapter 5, Neville was quoted regarding the relationship between creep and shrinkage of concrete. He stated that concrete which exhibits high shrinkage generally also shows a high creep. The results in this testing program showed that mortars with high creep generally had low shrinkage. The 1:2:9H mortar was the one exception. It was characterized as a mortar exhibiting higher creep than cement-rich mixes and one which shrank the most and was the last to cease shrinking.

At the beginning of this testing program it was supposed that shrinkage and creep were related to the quantity of lime in a mortar mix, in the sense that the richer the mix is in lime, the higher the values for creep and the lower the values for shrinkage. It was supposed that the ability of masonry walls to tolerate movement was attributed to those values. These hypotheses were based on the fact that lime-rich mortar in old masonry has shown a greater tolerance of structural movements. The case studies and test data, generally, confirm these suppositions, which were an explanation, now scientifically confirmed, of the commonly observed behavior of buildings over a long period of time.

In conclusion, creep can be assumed to be an important factor in the mechanism by which masonry walls accommodate movement without damage. The research suggests that a masonry wall should be constructed using the lowest strength (and thus highest creep) mortar which will satisfy the requirements of structural load and durability. The properties of a soft lime mortar appear to be such that stresses caused by thermal, moisture, and some settlement movements can be dissipated by creep. On the other hand, hard cement mortars inhibit movement to the degree that severe cracks and other damage can develop. Creep is a valuable attribute of mortars, contributing to the long-term survival of old buildings.

References and Notes

1. Through a chemical process, salt does attack Portland cement, causing mortar to expand and crack. Salt's affect on a non-cement mortar needs additional study to determine if and how salt affects hydraulic lime. Cecil C. Handisyde, Building Materials (London: The Architectural Press, 1958), p. 81.

2. BRE, Digest 160, 2.

3. BRE, Digest 160, 2.

4. David Lenczner, Movements in Buildings, 35.

Appendix 1: Lexicon of Mortar-related Terms

This lexicon was compiled with a two-fold purpose. It aims to give a historical view of the development of mortars and cements since Roman times by listing some of the surviving recipes. And, it aims to define all mortar-related words (e.g. types of lime) with the intent that the definitions clarify regional terminology and enable words to be understood internationally.

In completing this lexicon, work progressed smoothly on defining most general terms still in use today. However, detailed investigations into specific recipes were necessary. One problem that arose was that period treatises and magazines often referred to a mortar recipe as it the reader would know all about it. As a result, the source gave the barest of details on the product. Consequently it often took scant references from several works to completely and accurately define a recipe. Even then, only those recipes frequently spoken of in the sources used are listed. Details and information on the obscure mortars can be obtained from patent records or through such books as The Repertory of Arts.

The invention and patenting of mortars were popular in the late 1700s through the 1800s. Source material from this period, however, proved to provide little information other than statistics. Patent standards were low then and minimal details were supplied. It is unclear whether this lack of information resulted from it not being required or because inventors felt the need to retain the secret recipe for sole manufacturing rights and for protection after the patent's expiration. Nevertheless, these men did not rely too heavily on the protection supposedly given by the patent. Furthermore, low standards enabled many people to patent their ideas and theories, thus accounting tor the many patents on the subject.

Encyclopaedias and periodicals from 1800 onward were no better in providing complete information on mortar recipes than the patents. Usually, they mentioned the mortar's name and recipe briefly in a more general article on the subject, or simply used the recipes as space fillers on a page. The name of the inventor and the mortar's original date had to be sought elsewhere. Ideally, the information listed in these periodicals and other sources was coupled with a patent to give a fairly complete story. If a patent did not exist, in some instances an approximate date could be deduced from the date of the publication. Treatises and such periodicals as The Builder wrote on current events and often listed or spoke of new recipes. For lack of other information, these new recipes are given the dates of the works they were taken from.

This lexicon gives as much information as obtainable on the various aspects of mortar and cement. The authors of the sources used are listed at the end of each definition with the full details given in the Bibliography. Synonyms of terms are also listed, thus clarifying the different words used in other countries to describe the same thing. Finally, this lexicon was compiled to complement the text of this dissertation, particularly the historical chapters (1 - 3). Any reader confused by any term used or by predominantly American nomenclature should refer to this Appendix.

Adam's Cement: Also known as "Adam's New Invented Patent Stucco," Robert Adam (1728 - 1792) purchased John Liardet's (b.? - d.?) patent (British Patent #1040-1773) in about 1778, renamed it, and used it as his own. See Liardet's cement. (Clifton-Taylor; Melville)

Adam's New Invented Patent Stucco: See Adam's cement.

Additive: See Admixture.

Admixture: A substance other than aggregate, cement, lime, or water, added in small quantities to the mix to alter its properties. Accelerators, plasticizers, and air-entraining agents are admixtures, as well as pozzolanas and fibrous substances. British Standard 4049:1966 states that an admixture is added to a mix, but an additive is added to a binder. (BS 4049; Scott, Building)

Adobe: Also called "mud mortar," it is a mixture of earth, preferably argillaceous, and water, and is used in arid regions as a primary building material. Sun-dried adobe blocks are strong enough to serve as load-bearing masonry. (Sturgis)

Aggregate: Any granular material, such as sand, gravel, crushed stone, or iron blast-furnance slag, used with a cementing medium to form a mortar. It is usually the largest volumetric constituent of a mortar. Aggregates are divided into four groups: coarse, fine, heavyweight, and lightweight. See Sand and specific aggregates. (ASTM C-125)

Air Mortar: Any mortar that will not harden under water, and therefore is only suitable for use "in air." (Smeaton, Eddystone Lighthouse)

Air-slaked Lime: Quicklime that is exposed to the air in sufficient quantity to show signs of hydration. (ASTM C-51)

Alca Lime: A lime combining the plasticity and sand-carrying qualities of lime mortar while having the strength, hardness, and quicker set of gypsum plasters. It is composed of 85% hydrated lime and 15% specially prepared materials containing alumina and silica in such proportions as to combine and form bodies that contribute to the hardness, strength, and plasticity. This lime was new to the field in approximately 1943 and was packaged such that only sand and water needed to be added. It was to be used in place of lime mortar gauged with Portland cement. (Graham)

Aluminous Cement: Also known as "high aluminous cement," it is made by heating limestone and bauxite until the mix is molten, or occasionally is made by sintering. Aluminous and calcareous materials are fired to a completely molten state, then broken up and ground to a powder. The special properties of this cement are attributed to its chemical composition which includes a higher proportion of alumina than that found in Portland cements. The high alumina content is obtained by using the mineral, bauxite, instead of ordinary clay. It can be used to make concrete resistant to high temperatures, but will lose a considerable portion of its strength if used in temperatures over 86° F (30° C), or under hot and damp conditions. (Handisyde; Lea; Popovics)

Aquatic Lime: Lime that indurates in water. In Germany it was called "lime-for-the-water," and prior to 1814 'water lime' was the name for it in England. In approximately 1814, Louis J. Vicat (1786 - 1861) used the term 'hydraulic lime' to describe this type of lime, and it has been retained. (Payne)

Arenes: Certain argillaceous or loamy sand, particularly quartzose, containing irregular and unequal grains of yellow, red, and brown clays. It is usually found on the summits of rounded and elevated hills, or sometimes in white clay. (Spackman, Some Writers; Vicat)

Artificial Cements: Proprietary cements made by mixing limestone or chalk with clay or shale, and burning them at 2012 - 2372° F (1100 - 1300° C). The pioneer in this field was Baron Louis Bernard Guyton de Morveau (1737 - 1816) and some popular examples were Greaves' cement and Lithic cement. (Francis; Guyton de Morveau; Hudson, Building Materials)

Artificial Hydraulic Limes: Experiments to produce artificial limes began as early as 1774, but did not become popular until Vicat's time. The limes were prepared in two ways. The first, though expensive, was considered to make a perfect lime: slaked rich lime was mixed with a certain proportion of clay and then the compound was burned. This procedure put the lime through a double calcination, thus contributing to create a "perfect lime." The second methods consisted of mixing a soft calcareous material, such as chalk or tufa, with clays, burning the mix and then reducing the whole to a paste by grinding them together in a mill. Depending on the materials used, the proportions were generally 1 part of dry clay mixed with 4 parts of very pure rich lime in the first process, or in the second process with 7 parts of calcium carbonate. If the lime or carbonate contained any clay, a smaller proportion of clay was necessary. M.M. Brian and St. Leger were two manufacturers of this product and both were directed by Vicat. (Dancaster; Guyton de Morveau)

Artificial Stone: Also known as "terra cotta," this stone was defined by Peter Nicholson (1765 - 1844) as "a compound comprised of pipe-clay, stone-bottles, glass, flint." The mix was pounded together, burned, and sifted through a fine sieve, after which a small portion of silver sand was added. Water was added to the right consistency to make the mix ready for use. ("Pipe-clay" is fine white nearly pure kaolin or china clay, while "stone-bottles" refers to a more durable earthenware clay.) (Nicholson)

Ash: Unless defined in greater length, ash can be used to denote either wood ashes or volcanic tufa.

Ash Mortar: John Smeaton (1724 - 1792) in his 1813 edition of A Narrative...of the Eddystone Lighthouse states that this mortar was created by Lord Macclesfield and consisted of 2 bushels of fresh meagre lime and 3 bushels of wood ashes. It was recommended for use where continual wet-dry cycles occurred and was thought superior to trass mortar. (Lomax; Smeaton, Eddystone Lighthouse)

Aspdin's Portland Cement: Joseph Aspdin (1799 - 1855) accidently stumbled across this artificial cement in 1811 when he mixed water with clinker remaining after the lime and clay were removed from the kiln. It produced a cement that proved greater in strength than Roman cement and was named "Portland cement" as the color reminded Aspdin of Portland stone. Furthermore, the name had good advertising value as Smeaton had described Portland stone as strong and durable. It was patented as an artificial cement in 1824 (British Patent #5022-1824) and another version on June 7, 1825 (British Patent #5180-1825). After Joseph's death, his son William (1818 - 1866) continued processing the cement and this was later considered to be the forerunner of the Portland cement used today. See Blue green mass cement. (Cowan; Spackman, Calcareous Cements)

Asphalt: The name given to that portion of bitumen that is of a solid consistency while at ordinary temperature, and that is soluble in carbon disulphide. Asphalt consists mainly of the two hydrocarbons, petrolene and asphaltene. See Bitumen. (Dancaster)

Asphalt Mortar: A mastic prepared by crushing and grinding bituminous limestone to a powder. Then it is mixed with a quantity of mineral pitch or bitumen, usually about 15% bituminous mineral pitch. (Dancaster)

Atkinson's Cement: Invented by William Atkinson (1773 - 1839), his cement was considered inferior to Parker's cement. It was made from argillaceous limestone or from the shale beds of the Lias formation found on Lord Normanby's Mulgrave estate at Sandsend in Whitby, Yorkshire, England. This cement also was called 'Lord Normanby's cement' or 'Mulgrave cement' locally in Yorkshire, and known as 'Atkinson's cement' or 'Yorkshire cement' in London and the South of England. Some confusion exists over the name, Atkinson. Credit for this cement is given, in some sources, to Thomas Atkinson (1799? - 1863?) and in other sources, to William. As production began in 1811 at which time Thomas would only have been 12, the cement was probably invented by William, perhaps the father of Thomas. (Davey; Francis; Melville)

Backing Mortar: Smeaton in his narrative on the Eddystone lighthouse defined backing mortar as a mix of 8 parts of lime, 1 part of pozzolana, and 12 parts of sand. This same mix was recommended nearly 100 years later in 1848 by Peter Nicholson in his treatise, The Practical Builder. The word 'backing' refers to the position or location of the mortar, that situated behind the surface mortar and facing bricks. (Nicholson; Smeaton, Eddystone Lighthouse)

Bailey's Composition: A composition that produced a very hard and durable cement. It was made from stone lime that was burned and slaked immediately afterwards, then mixed with sharp, clean river sand in the proportion of 1:3 lime:sand. Nicholson referred to the composition as being "non-injurious" by even the severest winters and suggested that the lime used should always be limestone or carbonate of lime, never chalk, stored in airless containers and mixed with sand only shortly before use. (Loudon; Nicholson)

Base Hydraulique: French for hydraulic base, a term that Vicat and others used for hydraulic lime. Colonel Antoine Raucourt de Charleville (1799 - 1841) considered the best hydraulic lime to be composed of equal parts of pure caustic lime and other ingredients such as silica, alumina, and magnesia, as their chemical action gave birth to hydraulic properties. Both men believed the hydraulic properties lay in the use of silica, alumina, or magnesia as a base for the lime. (Vicat)

Bastard Stucco: An internal plaster stucco that contains a small portion of cow or ox hair. Although used as a finish coat, it is not worked up to a smooth surface. (Hodgson)

Bauxitland Cement: A cement considered to be a form of Portland cement, but with low silica, and high alumina and ferric oxide contents. It is produced by adding waste bauxite to a raw mix of Portland cement and is similar in strength to rapid-hardening Portland cement. Also called "Kuhl cement," the cement is popular in Germany, Austria, Czechoslovakia, and Japan. (Lea)

Beach Sand: A term used for soft sand, or sand with round, smooth grains. (Hinde)

Beale's Cement: Patented as a fire-proof cement, it consisted of 12 parts of chalk, 4 parts of lime, 4 parts of salt, 2 parts of Barnsey sand, 1 part of iron filings or dust and 1 part of blue or red clay. The ingredients were combined, ground, and then calcined. This cement gained enough popularity in the late nineteenth century to be published in a scientific cyclopaedia of the time. (Cooley; Spon)

Benson's Metallic Cement: A cement mix composed of Blue Lias lime with a metallic sand resembling pozzolana, but containing iron. It dates from approximately 1856. (Land and Building News)

Beton: French for 'concrete,' it is composed of an aggregate of pebbles or broken stones, embedded in a matrix of mortar. The mortar is either a lime mortar or a cement mortar. Beton with lime was used by the Romans. The reintroduction and use of this system was mistakenly credited by Major-General Sir Charles W. Pasley (1780 - 1861) to Sir Robert Smirke (1781 - 1867) and consisted of a mix ot 1:3 hydraulic lime:fine sand. Vicat thought all beton was destined for immersion in water. See Concrete. (Sayre; Vicat)

Beton-Coignet Artificial Stone: Invented by Francois Coignet (b.? - d.?), his artificial stone was composed of Portland cement, siliceous hydraulic lime, clean sand, and fresh water. Tiel lime was recommended for use as the hydraulic lime. The mix set quickly and was very strong. Its equivalent in the United States was a mix of Rosendale cement and sand, and also went by the name of "Beton-Coignet stone." See Rosendale cement. (Baker, Treatise; Chandler)

Binder: Material that fills the voids between the inert constituents of a mortar, and sets and hardens by a chemical process to form a continuous solid. It may or may not develop chemical bonds with the inert particles in the mortar and with the building units. Some surviving Roman and medieval mortar recipes containing lime, sand, and such organics as blood or eggs used these latter items as the binders for the sand. Based on the results obtained from analyses of ancient mortars and plasters, binders nearly always contain carbohydrates, albumen, or both. (Neuburger; Scott, Civil Engineering)

Bitumen: An inflammable mineral substance consisting mainly of hydrocarbons, such as naphtha, petroleum, and asphalt. The best is considered to include not only asphalt, but also the other liquid and solid hydrocarbons present in its crude form. It should be free from water and after being filtered, should not have more than 75% of earthly matters. Bitumen was used in ancient times (e.g. in Mesopotamia) by itself as a mortar and is still used today occasionally as a mortar or sealant. (Dancaster; Singer)

Black Mortar: The term dates back to at least 1532 when at Westminister Palace sea coal or smithy's dust was used in a lime-sand mortar base to produce a black-colored mortar in which to lay flint. This technique was reintroduced by the Victorians, although they used smithy's ashes and crushed clinkers in addition to dust and coal. (Graham; Salzman, Building...1540)

Blast-furnace Slag: A nonmetallic product of silicates and aluminosilicates of calcium turned into a molten mass with iron in a blast furnace. (ASTM C-125)

Blue Green Mass Cement: The name given to a sample of Aspdin's cement by Isaac C. Johnson (1811 - 1911) when it was analyzed by Dr. Andreas Ure on April 16, 1844. Johnson was a competitor of Aspdin and was trying to discover the secret behind the manufacture of the cement. It was found to contain 10% carbonate of lime, 22.24% lime, 45% phosphate of lime, 15% sulphate of lime, 2.5% soluble salts, 1% moisture, 1% alumina, 2.26% iron oxide, and a trace of sulphuric acid. The analysis never directly aided Johnson's attempts. (Spackman, Some Writers)

Blue Lias Cement: One of three Portland cements on the market in 1847, this cement was manufactured by Mr. Richard Greaves of Stratford-upon-Avon. It was made by mixing indurated clay or shale with blue lias lime, both being acquired from the same quarries. The former was broken and ground before being mixed with the latter which had previously been burned and slaked. The other two cements were Frost's New cement and Patent Lithic cement. (Davis, One Hundred Years)

Blue Lias Lime/Limestone: Often shortened to "Lias lime," this material came from the area between the south coast of Dorset and Lincolnshire, but is no longer available. Its blue color when freshly fractured was due to the presence of ferrous oxide, and depending on the location where quarried within this region, the composition varied in quantities of silica and alumina: from 8% aluminum silicate and 90% calcium carbonate to 64% aluminum silicate and 34% calcium carbonate. The best Blue Lias contained 16 - 20% aluminum silicate and was called "Aberthaw lime" (Smeaton used it at the Eddystone lighthouse). The lime had to be slaked for several days and ground, because there was insufficient free lime to bring about the disintegration of the clinker. Finally, the clinker was ground and then exposed to the air for 2 - 3 weeks before use. The end product was one of the best hydraulic limes on the market from Smeaton's time until its extinction in the mid-twentieth century. (Dancaster)

Blue Mortar: In a layman's guide produced in 1913 by Sears, Roebuck & Company, blue mortar was defined as a mix of 3:2:2 fine foundry ashes:ground stone lime:sand. (Hodgson)

Blunder: A lime free of alumina, but containing 9 - 40% silica sand. Blunder also implies that the lime is devoid of cementitious properties as it lacks alumina. (Burnell)

British Cement: A cement patented in 1822 by James Frost. See Frost's New Cement.

Brown Mortar: The 1913 Sears guide termed brown mortar as a mix of 1:2 lime:sand with a small quantity of hair added. It was recommended as a mortar for plastering. (Hodgson)

Bruyere's Cement: Recommended as a hydraulic cement, it was composed of 3:1 clay:slaked lime. The ingredients were ground to a powder after being exposed to a full red heat for three hours. This recipe was listed in a scientific cyclopaedia of 1880. (Cooley; Spon)

Builders' Sand: A term used for sharp sand, or sand with sharp, angular grains. (Hinde)

Caementa: Irregular pieces of stone or brick used as aggregate in Roman concrete. (McKay)

Calcite Limestone: Limestone containing less than 5% magnesium carbonate. (ASTM C-51)

Calc-sinter: Another name for "tufa" or "travertino." See Travertino. (Dancaster)

Calderwood Cement: Similar to Roman cement, it was made from limestone at Calder Glen, near Barrhead, Renfrewshire, Scotland. (Davey)

Carboniferous Limestone: Also called "mountain limestone," this stone produces a lime suitable for air mortar, but sometimes contains sufficient silica and alumina to produce hydraulic lime. Many beds are highly fossiliferous, and these are less suitable for the manufacture of lime. (Dancaster)

Carbonization: The reaction of atmospheric carbon dioxide with non-hydraulic lime mortar, causing it to harden into calcium carbonate. (Williams)

Casein Cements: Also known as "lime-albumen cements," they are composed of lime and albumen, the latter not necessarily meaning egg whites but possibly cheese. The lime should be free of gritty matter with at least 95% free calcium oxide. This is best achieved by sieving. Milk-of-lime is the best casein cement. The milk should sit before it is used, and only that milk-of-lime that passes through an 80 hole/inch sieve should be used. Casein cements are popular in rural areas. (Searle)

Cellular Basalt: Nicholson defined this material as "wakke" or "terrass." See Trass. (Lomax)

Cement: In the present age, this word is used for many types and varieties of mortars from Adam's cement or Roman cement to high alumina cement or low-heat Portland cement. Originally 'cement,' 'mortar,' and 'lime' were interchangeable, all used to describe the same building material. It was not until Portland cements and other stronger forms of mortar were invented that these words began to take different meanings. Then 'mortar' meant a lime-based mortar and 'cement' was applied to lime-free, very strong mortars. More recently, 'cement' has become a general term denoting a binding material of plastic consistency with adhesive properties and a hydraulic setting action. More specifically, 'cement' is a shortened name for Portland cement. Since the advent of Portland cements and the introduction of artificial elements to building mortars, cements have been separated and defined as either natural or artificial, the latter usually being the clinker from a kiln. Vicat defined cement as containing 40 - 60% clay and 60 - 40% lime.

In Late Latin or Old French forms, 'cement' designated powdered tiles and pottery. It was later classified as an artificial pozzolana, and its meaning has changed to denote mortar prepared by mixing three ingredients; but more recently it implies a single material. The 1397 edition of De Proprietatibus Rerum of Bartholomew Anglicus (translated by John Trevisa) defined cement: "Lyme...is a stone brent; by Medlynge thereof with sonde and water sement is made." (Chandler; Davey; Lea; Sayre; Vicat)

Cement-lime Mortar: A mortar defined in some treatises as a mix of 1:1:6 Portland cement:lime:sand. (Shertzer)

Cement Mortar: Like 'cement,' this term has a variety of meanings and can cause confusion as many treatise writers used their own definitions. Many treatises have been written on the subject and attempts have been made to give and promote the best proportions. For example, 'cement mortar' used below water consisted of 1:1 cement:sand, while that used above water was a mix of 1:2 cement:sand. The 1913 Sears catalog also defined cement mortar as a mix of 1:2 cement:sand. One author, Sayre, defined cement mortar as a mix using sand in some combination with Portland, natural, or slag cement. He stated that Portland cement was more frequently employed, but whichever material was used, the composition was stronger than commmon or lime mortar. Cement mortar does not spread easily; so he recommended adding lime or loam to achieve some plasticity. The mix with lime should not exceed 1:4 cement:lime nor be greater than 1:3 cement:lime, and once mixed thoroughly in a dry date it should be sprinkled with water. Today cement mortar more commonly refers to Portland cement mortar tempered with lime. 'Cement mortar' is the third of three categories used to define types of mortar. See Mortar. (Chandler; Hodgson; Sayre; Shertzer)

Cement Rock: A term used to define all very clayey limestones carrying from 50 - 80% lime carbonate with a correspondingly high percentage of argillaceous matter and less than 8% magnesium carbonate. It is a substance ideal for Portland cement if the argillaceous limestone is low in magnesia and contains 75 - 77% lime carbonate and 20% clayey materials such as silica, alumina, and iron oxide. (Eckel)

Cement Stones: See Septaria. (Davey)

Chalcedony Cement: A flint cement created by Henry Reid (b.? - d.?), it is comprised of 4 parts of 'slaked' lime, 1 part of powdered flints, and 12 parts of sand. Reid stated in his 1870 publication, Portland Cement, that flint cement produced a good hydraulic mortar. (Reid)

Chalk Lime: Occasionally called shell lime, a lime Nicholson recommended as a limestone substitute in his recipe for fine- and coarse-grained water cement, except that 2-1/2 lbs. of chalk lime was required in place of 2 lbs. of stone lime. The quantity and type of sand specified remained unchanged. (Bowyer, Handbook; Nicholson)

Chalk Marl: A substance found in the Cretaceous system ('creta' means chalk), the latest period of the Secondary geological era, and the lowest formation in the system. It is very impure and contains variable amounts of clay, silica, and iron oxide. Lime produced from chalk marl is known as "clunch lime," and is uncertain in quality and liable to shrink in setting, owing to the existence of an excess amount of clayey matter. (Dancaster)

Chaux de Theil: A limestone from Ardreche on the Rhone River. The silica in the limestone exists in a finely divided and soluble form and combines with the lime on burning. The amount of alumina present seldom exceeds 2%. The lime contains 65 - 75% calcium oxide, 20% silica, 2% alumina, and small quantities of magnesia, ferric oxide, and other impurities. (Dancaster)

Chunam: A rendering used in India due to the lack of limestone. A local practice, popular in the nineteenth century, it varied from region to region within the country. In the interior, chunam was prepared from kunkar nodules, which consist mainly of calcium carbonate mixed with a little clay into an impalpable powder. Once burned, it was mixed with coarse or fine siliceous sand and tempered thoroughly with water. Generally coarse syrup or molasses made from native sugar was added in small quantities; this ingredient retarded the too rapid drying of the freshly laid chunam in the torrid climate. On the sea coast of India, shells were burned and mixed with sand and then treated in the same manner as described above. Often the dry mix was boiled with molasses; the syrup produced was called "jaggree." This practice does not have much influence on the set. (Sayre)

Ciment Demi-lente: The French name for natural cements that are slow-setting: These are similar in character to natural Portland cements. (Eckel)

Ciment Grapier: The French name for cement composed of hard, unchanged limestone lumps. It is called "Grappier cement" in England and America. See Grapier. (Davey)

Ciment Prompt: The French name for natural cements which are normal or unaltered from their quarried state, or are quick-setting. (Eckel)

Cistern Cement: Published in 1843 in The Builder as a new product, it consisted of 2 parts of ashes, 3 parts of clay and 1 part of sand, all mixed with oil. It made a cement "as hard as marble and impenetrable by water." (The Builder)

Clay: A firm, fine-grained earth, plastic when wet, composed chiefly of hydrous aluminum silicate minerals. Vicat stated that clay was composed of silica and alumina, and adulterated by the presence of iron oxide, carbonate of lime and magnesia, sulphuret of iron, and partly decomposed vegetable combustible matter. He divided all clays into four classifications: refractory clays; fusible clays; effervescing or clayey marls; and ochrey clays, colored red or yellow by iron oxide. (Vicat; Webster)

Clinker: Sintered or fused ash from furnaces. In the manufacture of Portland cement, clinker is the product obtained after raw materials have been ground, mixed, and burnt. The clinker then is mixed with gypsum and ground to a powder to ultimately produce cement. (Popovics; Scott, Civil Engineering)

Clunch Lime: Lime produced from chalk marl. See Chalk marl. (Dancaster)

Coade Stone: Created in 1769 by John Bacon, a designer at Coade & Sealy of Lambeth, England, this artificial stone was resistant to weather and fire. Its basic material was kaolin, which was moulded before drying as was terra cotta. It retained its popularity through the Regency period, but was discontinued in 1840 due to the closure of Coade & Sealy and the fact that pre-cast concrete was finally available and cheaper. (Singer)

Coarse Aggregate: All granular material which does not pass through a 4.75 mm sieve. (ASTM C-125)

Coarse-grained Cement: Nicholson also called it "cross-grained cement" or "coarse-grained water-cement." It was made from 8 lbs. of coarse sand, 6 lbs. of fine sand, 2 lbs. of purified lime, and 2 lbs. of bone ash. The two types of sand were combined and wet with lime water. After the excess liquid was drained off, the purified lime was added to the wettest area. Then the bone ash was added. Nicholson stated that "the quicker and more perfectly these materials were mixed and beaten together and the sooner the cement thus formed was used, the better it would be." The main difference between this cement and common mortar is that this cement is "shorter" than mortar and dries sooner. The word 'short' means that this cement contains an excessive amount of sand. See Short. (Bowyer, Handbook; Nicholson)

Coarse-grained Water Cement: See Coarse-grained cement.

Coarse Mortar: The 1913 Sears guide defined coarse mortar as a mix of 1:4 lime:coarse gravelly sand. (Hodgson)

Coarse Sand: See Coarse aggregate.

Coarse Stuff: When used in reference to mortar, it is a wet mix of lime and sand; however in reference to plaster, stuff consists of a wet mix of lime and hair. (Bowyer, Handbook; Williams)

Colored Portland Cement: Ordinary Portland cement into which 3 - 10% of a chemically inert pigment, usually some metallic oxide, has been interground. For light colors, white Portland cement must be used as the base material. (Popovics)

Common Fat-Lime Mortar: A slight derivation of common mortar, it consists of 2:10 to 2:16 quicklime:sand with 3 parts of water. Fat lime should only be used when quicklime is unavailable. The excess amount of sand prevents heavy shrinkage. (Chandler)

Common Mastic: A mastic prepared from 20 parts of ground stone, 10 parts of silver sand or fine river sand, and 3 parts of litharge. Mix the ingredients and sieve them, using a fine sieve. The mastic may be kept for any length of time in a dry place. When required for use, gauge it with raw and boiled linseed oil in equal proportions until the mastic is the consistency of fine stuff. The more it is knocked up, the better it works. The addition of 3 parts of red lead is sometimes used to increase the tenacity of the mastic. (Hodgson)

Common Mortar: A mortar comprised of lime and sand mixed with water. 'Common' or 'lime mortar' is the first of three categories used to define types of mortar. See Mortar. (Nicholson)

Common Stucco: Recommended in the 1913 Sears guide, it is defined as a mix of 1:3 hydraulic lime:sand. See Stucco. (Hodgson)

Compo: The word has been used to define a variety of different types of mortar since the late eighteenth century. Roman cement was called "compo" by plasterers and was a stone substitute consisting of a mix of 2:3 septaria:grit sand. With the advent of Portland cement in the nineteenth century, the name was applied to a lime mortar with such extra additives as cow hair. It was the name given to any cement mortar and was termed such by Victorians, especially ecclesiologists, to indicate their contempt for the product. In the twentieth century, it is usually applied to lime mortar gauged with cement. British Standard #890 refers to compo as a restoration mortar which increases in strength without the lack of porosity. The standard defines it as a mix of 1:1:6 Portland cement:lime:sharp sand. Compo also is the name for raw flour or raw meal mortar. One of these items is mixed with lime to increase the binding power. (Audley; Bowyer, Handbook; Brunskill; Nicholson)

Compression: A state of stress in which the particles of a material are pushed one against the other, thus tending to shorten it.

Concrete: Like 'compo,' this word has had a variety of meanings. In ancient Rome, the word was used for a mix made with pozzolana. In India in the late nineteenth century, concrete was made using one of two recipes. One mix consisted of 4:1:1 broken stone:lime:surkhi. The other was a mix composed of 2 parts of broken stone and 1 part of a mortar of 2:1 sand (or surkhi) and lime. With the popularity of cement in the twentieth century, concrete took on a new meaning. It is considered to be a cement mixed with coarse and fine aggregate such as pebbles, crushed stone or brick, sand, and water, although lime occasionally replaced cement. Formerly, as seen in India, only lime was used. In 1850, George Burnell (1814 - 1868) defined concrete as a species of rough masonry made from small materials such as gravel or broken stone, and lime. (Burnell; Heath; Pevsner)

Coquina Concrete: Often shortened to 'coquina,' it may take two forms. Occasionally it is found naturally as a limestone composed of shells or fragments of shells from the Eocene Age loosely cemented by calcite. This coarse-textured, highly porous concrete was popular in St. Augustine, Florida. More commonly, 'coquina' refers to a mix of lime (obtained from burnt shells), coquina shells, and sand, all mixed into a mortar by man, not nature. The mix varied according to the strength it had to maintain. For compressive stress, a mix of 1:3:3 cement:sand:shell (shell that passed through a 1/2 inch mesh) was used. For tensile stress, the mix was 1:2:3 cement:sand:shell. And for mortar which would be under unusual stress, a mix of 1:1:2 cement:sand:shell was proposed. Coquina mortar is still used in Florida, particularly in St. Augustine. (Chandler)

Creep: The slow strain in a loaded material in addition to the elastic or instantaneous strain. It is a gradually increasing viscous deformation calculated by subtracting the instantaneous strain from the total strain.

Creep Recovery: The slow recovery of deformation which follows elastic recovery.

Cross-grained Cement: See Coarse-grained cement.

Dehl's Cement: See Dihl's cement.

Dense: A word used to describe a hard or strong impervious mortar such as cement. (Williams)

Depeter: A form of rough cast where gravel is pressed into the cast by hand. (Hodgson)

Dihl's Cement: Also called "Dihl's (or Dehl's) mastic cement," it was invented by Christopher Dihl (b.? - d.?) in 1815 (British Patent #3872-1815) with a similar version patented the following year (#4033-1816). The cement was made by taking linseed oil rendered dry by boiling with litharge and mixing it with porcelain clay to a fine powder. The product was colored by the addition of ground bricks and pottery. To aid its adhesion, Dihl recommended the addition of turpentine oil to form a thin version of his cement. Burnell stated that the cement's composition was a secret, but that the mix consisted of pounded brick dust or well-burnt clay with litharge, the red protoxide of lead, and with some extraneous matter. As Dihl's patent never gave the exact proportions, only close approximations can be made from analysis. La Rochelle mastic from France was said to be very similar to "mastic de Dihl." See La Rochelle mastic. (Burnell; Dancaster; Davey; Melville)

Dobbs' Water-proof Cement, Mortar, or Stucco: Patented by Edgar Dobbs (b.? - d.?) on August 2, 1810, it was a mix of water, lime carbonates such as chalk, lime, marble, oysters, shells, and earths and one or more of the following: clay, loam, mud, shale, dirt, dust, soil, ochre, metallic oxides, ores, pyrites, stones, ashes, or earths. The lime was slaked and ground, then mixed with the other ingredients. Water was added until the mix became plastic, then the excess water was decanted. The mass was cut into pieces, then burned and ground. In particular, Dobbs recommended a mix of 6 parts by weight of chalk, 2 parts of clay, and 2 parts of ash. If lime was used in lieu of chalk, 3 parts should be employed. For a quicker set, more lime was added; for a slower set, more clay and ash were used. (Repertory of Arts)

Dolomite: Also known as "magnesian limestone" or "dolostone," a stone is dolomitic or magnesian if it contains 5 - 46% of magnesium carbonate, or 35 - 46% and 5 - 35% respectively. Typical dolomite, $CaCO_3.MgCO_3$, contains 45 - 66% of magnesium carbonate. High levels of magnesium carbonate in a limestone indicate that the stone is not suitable for lime manufacture except for special purposes. The magnesia slakes and hardens in water, but absorbs water slower than lime. Should lime be produced from this unsuitable limestone, it can be expected that the lime will not slake evenly and will be liable to crack after setting. (ASTM C-51; Dancaster)

Dolomitic Lime/Limestone: Limes that are slow to set, take three months to cure, and are equal to a high calcium lime in the manner in which they set. They are obtained from dolomitic or magnesian limestones containing 35 - 46% of magnesium carbonate and are used in mortars only when the presence of magnesia is acceptable. See Dolomite. (ASTM C-51; Bowyer, Handbook; Dancaster; Lazell)

Dough Stone: Another name for "terrass stone" or "trass." See Trass. (Smeaton, Diary)

Dove Stone: Also spelled 'duifsteen,' it is better known as "trass." See Trass. (Smeaton, Diary)

Drift Sand: Also known as "pit sand," "fossil sand," or "quarry stone," this sand consists chiefly of hard quartzose flat-faced grains with sharp angles. (Nicholson)

Drying Shrinkage: The irreversible deformation of mortar during drying after first setting.

Eddystone Mortar: In discussing mortar, Nicholson briefly referred to the mortar Smeaton used in building the Eddystone lighthouse. Three mixes of lime:pozzolana:sand were originally considered: 2:2:0, 2:1:1, and 2:1:3. Smeaton carried out experiments on those mixes and found that a durable, hydraulic lime mortar was produced when Aberthaw lime and Civita Vecchia pozzolana were used. A merchant in Plymouth had imported the pozzolana from Italy in the hope that he could sell it to the builders of Westminster Bridge; the material was not sold and was stored in Plymouth until a new buyer could be found. Based on his testing results, Smeaton chose a 1:1 mixture of Aberthaw lime and Civita Vecchia pozzolana for the actual building of the lighthouse. To ensure maximal possible strength and durability, no sand was added. (Nicholson; Smeaton, Eddystone Lighthouse)

Edisbury's "Glassis": Considered to be the earliest known stucco, it was patented in 1677 by a Mr. Edisbury. (Clifton-Taylor)

Eisen Portland Cement: Also known as "iron Portland cement," this particular type of Portland cement is similar to the Portland blast-furnace cement made in Germany. It is made by mixing slag with proportioned limestone, and then grinding and burning it to clinkering temperature. The German specifications for Eisen cement require that not more than 30% of the cement consist of granulated slag. (Lea)

Elastic Deformation: The deformation of a material under load, which recovered when the load is removed.

Elastic Recovery: The strain recovered on removal of load. In laboratory experiments, the elastic recovery is approximated by the recovery measured during an arbitrary short time; in this study the time is defined as one minute.

Elastic Strain: The strain, caused by an applied stress, that may be recovered when the stress is removed. In laboratory experiments, the elastic strain is approximated by the strain measured during an arbitrary short time; in this study the time is defined as one minute.

Emerton's Cement: See Oil mastics.

Eminently Hydraulic Limes: The fifth of five classes used to define limes, or the third of three classes used to define hydraulic limes. In both cases, these refer to limes made from clayey limestones containing 4 - 7% of combined silica. The limes set within three to four days after immersion; and after one month, the limes are quite hard and capable of resisting the solvent action ot running water. After six months have passed, they perform like harder, natural limestones. See Lime. (Dancaster; Davey)

Emulsion: Drops of one liquid suspended in another liquid, or a film around globules to keep them from coalescing. The drops should be small so that they will stay suspended and form a stable emulsion. (Gettens)

Erz Cement: Better known as "Iron ore cement." See Iron ore cement. (Lea)

Extra Rapid Hardening Portland Cement: Characterized by its rapid initial set and fast rate of hardening, it is useful for concreting in cold weather and also for work where very high early strength is required. It has a greater shrinkage than ordinary cement and because of its fast initial set, it must be placed into its final position immediately after mixing, preferably within fifteen minutes. (Handisyde)

Face Mortar: Unlike backing mortar, it is used on the face or visible joints of a wall. Nicholson defined this mortar as a mix of either 2:1:3 or 4:1:6 lime:pozzolana:sand. (Nicholson)

Fat Lime: Also known as "rich lime," it is the purest of limes with not more than 6% of silica, alumina, and impurities. Burnell defined rich limes as limes containing 1 - 6% of silex, alumina, iron, and magnesia, all either separately or in combination, and listed rich limes as the first of five classes of limes. Fat lime also can be termed "high-calcium lime" as it usually contains 95% or more of calcium oxide. With the addition of water, fat lime slakes rapidly with the evolution of a considerable amount of heat. The lumps then break down to form lime putty. Repeated exposure to pure water causes the lime to deteriorate. Vicat classified rich limes or "non-hydraulic" limes as those limes with less than 10% of foreign matter. Rich or fat limes are most commonly made from white marble, white chalk, pure limestone, or oyster shells. One source stated that two advantages to using fat lime over cement in a mortar are that walls can be built faster because the lime is easier to work than cement; and larger amounts of lime can be prepared for use without worrying about it drying up quickly. (Bowyer, Handbook; Burnell; Dancaster; Davey; Lea; Searle; Vicat)

Fatty Mortar: A sticky mortar having an insufficient amount of sand. It is a workable, cohesive mix that sticks or hangs on the trowel. (Graham; Williams)

Fibrous Plaster: Occasionally called "Staff plaster," it is ornamental in character and is used for temporary buildings or exhibits. The plaster is toughened and bound together by means of tow, or occasionally asbestos, slag wool, or coke breeze, and is fixed upon a backing of very coarse, open canvas called "scrim." Any necessary moulds for the plaster are made of gelatin on a plaster core. (Dancaster)

Filler: A fine powder of inert material which fills some of the voids between sand and other coarse particles in a mortar. It undergoes no chemical reactions as the mortar sets, but if used without a binder may stiffen considerably by drying. (Scott, Building).

Fine Aggregate: Granular material which passes completely through a 9.5mm sieve and almost entirely through a 4.75mm sieve, but is retained on a 75 um sieve. (ASTM C-125)

Fine Sand: See Fine aggregate.

Fine Stuff: The name given to lime which is slaked and in a semi-fluid state. Nicholson stated that fine stuff was a pure lime, slaked with a portion of water, and afterwards well saturated with water. It was put into tubs in a semi-fluid state where it was allowed to settle and the water to evaporate. Prior to use, a small proportion of hair was sometimes added. Today, fine stuff is the name usually given to a pure lime putty with no hair added. The 1913 Sears guide recommended a mix of 1:3 fine stuff:sand for use. (Bowyer, Handbook; Hodgson; Nicholson)

Fine-grained Cement: Also called "fine-grained water cement", Nicholson stated that it consisted of 98 lbs. of fine sand, wetted with lime water. Then, 15 lbs. of purified lime and 14 lbs. of bone ash were added. The main difference between this cement and coarse-grained cement was that one more pound of lime was required if the greater part of the fine sand was as fine as Lynn sand. This cement was recommended as a finish coat. (Bowyer, Handbook; Nicholson)

Flare Lime: Also termed "stone lime," it refers to lime produced from gray chalk found in the Cretaceous system between chalk marl and upper or white chalk. The name 'flare' was derived from the manner of burning the chalk. (Dancaster)

Ford's Silicate Stone: An artificial stone composed of 18:1 fine sand:chalk lime. The two ingredients were rammed into a mould and boiling water poured over it to slake the lime. The resulting stone was homogenous, easy to work, and durable. (Searle)

Fossiciae: The Roman word for pit sand containing some alumina. (Cowan)

Fossil Sand: Sand that does not come from riverbeds. See Drift sand. (Vicat)

Frear Stone: An artificial stone made from a mix of 2:5 Portland cement:siliceous sand. The sand is moistened with an alkali solution of gum shellac of sufficient strength to furnish 1 ounce of shellac per cubic foot of stone. Then the Portland cement is added. The shellac adds to early strength, but later may decay and cause weakness within the stone. (Baker, Treatise)

French "Grappier" Cement: Also known as "ciment grapier" or "grappier cement;" this cement is made from ground sinter lumps. Sinter is obtained by burning hydraulic limes at very high temperatures, causing the lime to sinter. Upon grinding, the lumps form grapier, which is similar to natural cements. See Grapier. (Lea)

Frost's Artificial Cement: Patented by James Frost (17?? - 18??) in 1811, this cement was very similar to Roman cement except that the ingredients were only partially mixed; and being inferior to Roman cement, it cost less. It was made from a mix of 2:1 chalk:Medway mud. (Davey; Lea)

Frost's New Cement, Artificial Stone, or British Cement: In 1822 Frost patented a second cement called "British cement" (British Patent #4679-1822) using selected limes and marls, particularly those containing magnesium as they were found to be free of any mix of alumina or argillaceous earth. They did, however, contain 9 - 40% of siliceous earth, silica, or a combination of silica and iron oxides, the silica being in excess. The lime or marl was calcined until all carbonic acid was expelled and then stored dry. Frost recommended that just prior to use it should be mixed to the consistency of common mortar with clean siliceous sand and applied instantly. This type of cement was often called "blunder," referring to a lime free of alumina, but containing 9 - 40% of silica sand. It also meant that it was devoid of cementitious properties. In 1825, Frost established cement works at Swanscombe, Kent, England, for the purpose of manufacturing his cement. It was not successful, and in 1833 the works passed into the hands of John Bazolay White, the forerunner of Associated Portland Cement Manufacturers Limited. (Francis; Spackman, Calcareous Cements)

Frost's Second Patent: Despite its name, this was the third patent with the Frost name, however, it was the second in a series published after 1812. There was no specific name give to this cement patented (British Patent #4772-1823) in 1823, so it was simply called "Frost's Second Patent." Rather than describing a new cement, it was devoted to a process of calcining and preparing calcareous substances for the purposes of forming cement. Unlike his first two patents, this one was of a general nature. (Spackman, Calcareous Cements)

Gad's Cement: Recommended for work that was required to harden under water, it was made from a mix of 1:1 clay:iron oxide. They were mixed and made into a stiff paste using boiled oil. The recipe dates from the 1880s. (Spon)

Gauged: Modified by the addition of an additional material to the mix. For example, lime mortar can be gauged with cement, or dry components can be gauged with water. (Williams)

Gauge Mortar: Mortar prepared for rapid setting. It is made with plaster of Paris, either pure or in combination with sand. (Sturgis)

Gauge Stuff: Mortar consisting of 3:1 fine-stuff:plaster of Paris. The materials are mixed together with water, small quantities at a time, rendering the mortar more susceptible to adhesion and setting. The mortar is used for forming cornices and mouldings. (Bowyer, Handbook)

German Cement: Patented by Matthew Fullwood (b.? - d.?) on May 6, 1828, it was a mastic composed of: 1 ton of Painswick stone, 1/2 ton of Painswick rag stone, 1/2 ton of Bisley stone, and 1 ton of Black Rock stone from Clifton, near Bristol. These stones were burned and ground, then mixed with water to form a lighter colored composition than Roman cement. The color could be lightened by further calcination without deteriorating adherent qualities. (Repertory of Arts)

German Cements: By 1875, cements from Germany had proved to be the best on the market. Two popular German cements still in use are Eisen Portland cement and Hochofen cement. See Eisen Portland cement and

Hochofen cement. (Hudson, Building Materials)

Gibbs' Cement: Patented in 1850, it was composed of natural, argillaceous marls and marly limestones (also called "marl stones"), which contained admixtures of lime, silica, and alumina suitable for the manufacture of artificial stones and hydraulic cements. Joseph Gibbs (b.? - d.?) recommended that calcination be prolonged as long as possible to avoid the commencement of vitrification which would destroy the adhesive properties of the cement. (Cooley)

Grapier, or Grappier: Grapiers are hard sinter lumps which consist of unchanged limestone and calcium silicates. When the lumps are ground, they have value as cementing materials. Grapiers used in cements are called "ciment grapier" in France and "grappier cement" in Britain and America. One example is La Farge cement, used largely in the United States as a non-staining cement. (Dancaster; Lea)

Grappier Cement: The British and American name for cements made from grapier. See Grapier. (Dancaster)

Gravel: A coarse aggregate formed by the natural disintegration and abrasion of rock. (ASTM C-125)

Gray Chalk: Another name for lower chalk, it is found between the chalk marl and upper or white chalk in the Cretaceous sytem. Gray chalk is less pure than white, and layers contain from 5 - 15% of silica, alumina, and iron oxide. Lime produced from this chalk is called "stone lime" or "flare lime," but often also named after the area of origin: Dorking lime, Halling lime, Gray stone, Medway, etc. Gray chalk slakes with less vigor than white chalk, and is liable to be overburnt. (Dancaster)

Granulated Blast-furnace Slag: The product obtained by the rapid chilling of a basic or high lime slag as it emerges from the blast furnace. It is a friable, light, porous product. (Lea)

Greaves' Cement: Richard Greaves (b.? - d.?) manufactured his artificial cement in the mid-1800s and claimed it was "a powerful water cement." It was made by mixing a proportion of indurated clay or shale with blue lias lime. The clay or shale was broken and ground, and the lime was burned and slaked. (Francis)

Grout: A fluid or semi-fluid cement slurry or a slurry made with other materials for pouring into the joints of masonry. (Scott, Civil Engineering)

Gypsum: A mineral consisting of hydrated calcium sulfate, $CaSO_4.2H_2O$, or calcium sulfate dihydrate. (ASTM C-11)

Gypsum Cements: Also called "marble cements," these cements contained the constituent, gypsum. Some popular examples were Parian cement, Martin's cement, and Keene's cement. (Francis)

Gypsum Stucco: See Plaster of Paris.

Haired Putty: A composition of fine lime putty and well-beaten white hair. The hair was thoroughly mixed with the putty to toughen it and prevent cracking. Haired putty was formerly used extensively as a setting coat in districts where the local lime was of a strong or hydraulic nature. It was not readily manipulated when mixed with sand to be used as setting stuff. (Hodgson)

Half Cement Mortar: The combination of a lime mortar and a cement mortar. Chandler in his Notes on Limes, Cements, Mortars, and Concretes defined lime mortar as 1 bbl. of lime, 5 - 8 bbls. of sand, and 1-1/2 bbls. of water, and cement mortar as 1 bbl. of cement, 3 bbls. of sand, and 1/2 - 3/4 bbl. of water. Half cement mortar was therefore 1 bbl. of lime, 1 bbl. of cement, 8 - 11 bbls. of sand, and 2 - 2-1/4 bbls. of water. (Chandler)

Hamelin's Cement: Also known as Hamelin's Mastic, Peter Hamelin (b.? - d.?) patented his cement on July 19, 1817 (British Patent #4417-1817). It consisted of sand, pulverized stone, china, and pottery shard, to which were added oxides of lead such as litharge, gray oxide, and minium, all reduced to powder. Then pulverized glass or flint were added, and the whole was intimately incorporated with linseed oil. The proportions of the ingredients were: to any given weight of sand or pulverized pottery were added two-thirds of the weight of pulverized Portland, Bath, or any other stone of the same nature. Then to every 550 lbs. of mixture were added 40 lbs. of litharge, 2 lbs. of pulverized glass or flint, 1 lb. of minium, and 2 lbs. of gray lead oxide. It was thoroughly mixed together and sifted through a sieve, the fineness of which was based on the intended use of the cement. Just prior to use, 1 quart of linseed oil was added to every 30 lbs. of cement, and well mixed together. Still in use today, this cement is also called "Hamelin's mastic" and is similar to Loriot's cement. One source gave the following mix for Hamelin's cement: 50 parts of siliceous sand, 50 parts of lime wash, and 9 parts of litharge, all ground up with linseed oil. Although these proportions vary from those listed in the patent, the mix is similar. (Davey; Hodgson; Melville)

Hard: See Strong.

Heavyweight Aggregate: An aggregate of high density, such as barite, limonite, iron, and steel. (ASTM C-125)

Higgins' Patent Cement, or Stucco: Patented in 1779 by Dr. Bryan Higgins (1737?- 1820), this cement was made from 56 lbs. of pure coarse sand, 42 lbs. of pure fine sand, 14 lbs. of pure fresh burnt lime, and 14 lbs. of bone ash. Higgins recommended that the lime be slaked by immersion. The cement was also called "Higgins' Patent Stucco." (The Builder; Vicat)

Higgins' Water Cement, or Stucco: Dr. Bryan Higgins patented this cement on January 8, 1777 (British Patent #1207-1777). The patent does not describe the cement. (Spackman, Some Writers)

High Alumina Cement: See Aluminous cement.

High Calcium Lime: See Fat lime.

High Calcium Limestone: Limestone containing less than 5% of magnesium carbonate. (ASTM C-51)

Hochofen Cement: Similar to Eisen Portland cement, it is a popular German cement containing not more than 85% of granulated slag. (Lea)

Hydrated Lime: Any lime processed to a dry powder. It is a dry, flocculent powder resulting from the slaking of quicklime by mechanical means with an amount of water which is sufficient to satisfy the calcium oxide, but insufficient to make a plaster or putty. Hydrated lime consists of calcium hydroxide alone or with magnesium oxide or magnesium hydroxide. This lime is free from the tendencies to pop, pit, or disintegrate. The addition of 15% of cement decreases its permeability to water; reduces the chance ot cracking due to shrinkage; increases the plasticity of the mortar, thus preventing separation of sand, stone, and cement, and causes the mix to flow and fill joints more readily. Hydrated lime has occasionally been called "limoid." One source states that the advantages for its use are: it is easy to store; it requires no slaking; it is uniform in quality; and it has to give more strength to a mortar than slaked lime made by hand. (Dancaster; Graham; Scott, Civil Engineering; Searle; Williams)

Hydraulic Hydrated Lime: A hydrated, dry, cementitious product obtained by calcining limestone, containing silica and alumina, to a temperature just short of fusion to form sufficient free lime (calcium oxide) to permit hydration. Simultaneously, the calcium silicates are left unhydrated so as to produce a dry hydraulic powder. (ASTM C-51)

Hydraulic Lime: An impure lime burnt from limestone containing a percentage of clay materials which, when used in mortar, allows the mortar to set, not solely by the evaporation of the water in the mix, but also by chemical action. The limestone contains alumina and silica, both found in clay, which combine with the lime during burning to create hydraulic properties. The higher the alumina and silica content, the lower is the heat involved. Burnell stated that hydraulic limes contained 20 - 30% of silica, magnesia, alumina, and iron oxides, half of this percentage being silex. Vicat, who is credited with naming these limes "hydraulic," said that they contained 10 - 34% of clay and 90 - 66% of lime. Others said that the limes contained at least 8 - 10% of combined silica. Hydraulic limes set after six to eight days' immersion and continue to harden up for to twelve months, although the greater part is achieved by six months. At that time, water is no longer able to erode the lime even when reworked. The strongest is classified as "eminently hydraulic" and the weakest as "feebly hydraulic." It is used as a setting agent, and is treated and stored like a cement. See Lime. (Bowyer, Handbook; Burnell; Dancaster; Davey; Lea; Vicat; Williams)

Inert: A word used to describe those materials which have little or no chemical reaction with lime. It is one of four classifications given by Vicat to materials' interaction with lime. See Lime. (Burnell; Vicat)

Iron Ore Cement: Also called "Erz cement," it is a Portland cement made near Hamburg, Germany. The clay and shale found in ordinary Portland cement are replaced with iron ore. It has high ferric oxide and low alumina contents, is slow in setting and hardening, and is more resistant to sea water than normal Portland cement. (Lea)

Jaggree: See Chunam.

John's Cement: Made by Johns & Co. of Plymouth, this oil cement was made from linseed oil, resin and powdered sandstone of the oolite formation imported from Rouen, France. The company recommended that it be mixed with three parts of sand for the best results. (Francis)

Kahl's Patent Plaster: A plaster containing 35% of sawdust, 35% of sand, 10% of plaster, 10% of glue, and 10% of whiting. The sawdust is used in lieu of hair. It was patented in America in the late 1800s. (Hodgson)

Kankar: Also spelled 'kunkar,' it is a nodule found on the plains of northern India and consists mainly of calcium carbonate. It is a calcareous, concretionary deposit formed in alluvial soil from carbonate of lime held in solution. (Dancaster; Heath)

Kankar Lime: Lime made by calcining kankar with charcoal. (Heath)

Keene's Cement: Still popular today, it first appeared in 1836 and was recommended for use as a plaster. Basically, it is burnt gypsum. The burned lumps or dehydrated lime sulphate are dipped in a solution of alum or aluminium sulphate and then dried. It then is burnt again at 932° F (500° C) and ground. Compared to other plasters, it sets rapidly within several hours, is hard, dense and durable, but is expensive. (ASTM C-11; Brunskill; Dancaster; Graham)

Knocking Up: Reworking coarse stuff or mortar in order to restore workability. (Williams)

Kuhl Cement: See Bauxitland cement.

La Farge Cement: A "non-staining" cement used largely in the United States and considered to be one of the better known grapier cements. See Grapier. (Dancaster)

La Rochelle Mastic: In 1826 in La Rochelle, France, city engineers used this mastic and claimed that it was similar to "Dihl's mastic." It was made by mixing by volume 196 parts of siliceous sand, 196 parts of pulverized calcareous stone, 1 part (of stone and sand's combined weight) of litharge, and 2 parts (of the total weight) of linseed oil. Dried in an oven, the mastic was mixed with the linseed oil just prior to use. See Loriot's cement. (Burnell)

Lean Lime: Also known as "poor lime," Burnell defined this lime as containing 15 - 30% of silica, magnesia, iron oxides, and manganese. It slakes slowly with little evolution of heat. It does not harden under water any more than rich lime, and therefore is distinguished from hydraulic lime, which also slakes slowly with little increase in volume, but sets under water. When lean lime is repeatedly washed with pure water, a residue of insoluble matter is always left behind. Nicholson stated that this lime does not form a good plastic putty. (Bowyer, Handbook; Burnell; Dancaster; Nicholson)

Lean Mortar: Mortar that does not adhere to the trowel due to the presence of too much sand. (Graham)

Liardet's Cement: John Liardet (b.? - d.?), a Swiss, obtained a British patent (#1040-1773) for his cement in 1773. It was the second mastic introduced on the market and achieved its popularity through Robert Adam. Adam purchased Liardet's patent and renamed it "Adam's cement" or "Adam's new invented patent stucco." It was manufactured at Lambeth and consisted of terra cotta made from certain clays and sand, and a drying oil. In 1776, Liardet filed another patent with more detailed specification. "For the first coat, 21 lbs whiting or shells or plaster of paris or any calcareous matter calcined and pulverized. Add white or red lead at pleasure diminishing from the other materials in relation to the amount added. Mix with 4 quarts of oil in a grinding mill then mix and beat up well with 28 quarts of sand or marble or pounded stone or brick dust or any kind of mineral powder. For the second coat, 16-1/2 lbs whiting or other material as previously specified. Add 16-1/2 lbs white or red lead. Mix with 6 quarts of oil in a grinding mill, then mix and beat up with 30 quarts of sand, gravel or mineral powder." See Adam's cement. (Clifton-Taylor; Francis; Melville)

Lias Lime Mortar: The 1913 Sears guide defined this mortar as a mix of 1:2 Lias lime:sand. See Blue Lias lime. (Hodgson)

Lightweight Aggregate: All aggregates of low density, such as sintered clay, slate, vermiculite, tufa, and sintered fly ash. (ASTM C-125)

Lime: Chemically known as $CaCO_3$. A traditional binding material for mortar, it is made from naturally-occurring items found in a variety of forms in the earth. Many people have tried to classify limes. Vicat divided limes into five categories based on their percentage of clay: 'rich limes' contained 1 - 6%; 'poor limes' had 15 - 30%; 'moderately hydraulic limes' contained 8 - 12%; 'hydraulic limes' had 20 - 30% with half of that being silex; and 'eminently hydraulic limes' contained 11 - 25% of combined silica. This classification is still used today. The definitions of each of these five classes have been expanded to include setting time and the solvent action of water. Vicat touched on this latter subject separately and created more categories based on materials' reaction with lime. He divided lime into four categories: very energetic; simply energetic; slightly energetic; and inert. (Many of the different types of lime or calcium carbonate are listed separately in this lexicon and are explained further under the specific names.) (Vicat)

Lime Cement: Lime mixed with sand so as to form a mortar or plaster. It is used as a cementing agent. (Searle)

Lime in the Stone: This phrase refers to limestone after burning, but before grinding or pulverizing. (Shelgren)

Lime Mortar: A mortar made from lime putty, but the proportions and ingredients vary with the author or the conditions under which it is to be used. Some recommend a 1:4 lime:sand. However, the most popular is the one given us by Vitruvius: 1:2 - 3. He suggested that lime be used in a 1:2 mix if the sand was from a river, and in a 1:3 mix if the sand was from a pit. Until the advent of Portland cement and similar cements, Vitruvius's recipe was recommended in many treatises. Lime mortar is the first of three categories for defining mortar. See Mortar. (ASTM C-51; Hodgson; Shertzer; Vitruvius).

Lime Putty: The plastic material resulting from slaking quicklime with an excess of water, or by adding hydrated lime powder to water. The putty should be allowed to stand for at least three months before it is used. The finest putty from the sieve is retained for putty; the rest is often used for coarse stuff. It may be kept for a indefinite amount of time without injury if it is protected from the atmosphere. Therefore, it should be covered up to resist the action of the air, principally the absorption of carbon dioxide. If absorption occurs, the lime becomes slightly carbonated and loses much of its causticity and, consequently, its binding and hardening properties. Today, traditional fine stuff is considered to be pure lime putty with no hair added. (ASTM C-51; Bowyer, Handbook; Williams)

Lime Wash: Two recipes were found for lime wash. A mix of 50 lbs.:15 lbs.:7-1/2 gal. hydrated lime:common salt:water was recommended for exterior work. And for interior work, a mix of 50 lbs.:7 gal. hydrated lime:water was suggested. Before application, it was suggested that the latter ingredients be mixed with 3 lbs. of glue in water. (Searle)

Lime Water: Stone lime, having passed through a sieve, mixed with water at the ratio of one ounce per gallon. The lime is slaked by plunging it into water, removing it, and plunging it in again. This system is repeated until all the lime is wet. Lime wash is used when scouring and trowelling setting stuff to harden the surface. (Hodgson; LaFever)

Lime-albumen Cement: Also known as "casein cement," it is made by mixing finely ground or hydrated lime with sufficient egg white to obtain a paste. (Searle)

Lime-cement Mortar: Many authors list a variety of mixes for this mortar: 1:1/2:5; 1:1:6 - 7; 1:1-1/2:8; and 1:2:10 cement:lime:sand. Today, British agencies such as the Scottish Development Department or the Directorate of Ancient Monuments use the mixes: 1:1:6; 1:2:9; and 1:3:12 cement:lime:sand. Occasionally this mortar is defined as a lime mortar tempered with Portland cement. On the other hand, these mixes are often called "cement-lime mortars," more in keeping with the order in which the ingredients are listed. (Filor; Searle; Shertzer)

Lime-for-the-water: The German name for aquatic lime or hydraulic lime. See Hydraulic lime. (Payne)

Lime-glue Cement: An adhesive made from a mix of 1/2 oz. of slaked or hydrated lime, 2 oz. of sugar, and 6 fl. oz. of water. After combining these ingredients, they are heated for two hours at 149° F (65° C). Then, 1/5 (of the mix's weight) of glue was added. (Searle)

Limestone: Of sedimentary origin, this stone is composed of calcium carbonate or the mineral, calcite, or a double carbonate of calcium and magnesium. A limestone can be calcitic, dolomitic, magnesian, dolomite, or high-calcium. See specific limestone. Limestones in which silica is insufficient to convert caustic lime into calcium silicate are liable to swell in setting and dislocate masonry. Those in which alumina is in excess are liable to shrink, crack and crumble away on exposure to weather. Highly fossiliferous limestones are liable to produce limes of uncertain quality which slake unevenly or retain their avidity for water. In either case, limes from these latter stones swell and disintegrate the mass around them, properties which are due to the presence of calcium phosphate of which fossils are largely composed. (ASTM C-51; Burnell; Dancaster; Davey; Williams)

Litharge: Also known as lead monoxide, litharge is a drier and pigment of pale yellow to brown color. (Scott, Building)

Litharge Mastic: Invented about 1815 by Bernard Thenard (b.? - d.?), it was made by mixing 93 parts of pulverized burnt brick or clay with 7 parts of litharge, and grinding it to a very fine powder. Pure linseed oil was added just prior to use to reduce the mastic to a plaster consistency. It was also called "Thenard's Unchangeable cement." (Burnell; Dancaster; Repertory of Arts)

Lithic Cement: Introducted in 1841 by the firm of Evans & Nicholson of Manchester, this artificial cement used lime from residual matter or from the waste of certain chemical works. Major-General Pasley spoke of this and other artificial cements in his treatise on limes and cements. (Francis)

Load: A force applied to a body of material.

Loam: Earth composed of clay and sand, or a fertile soil consisting of clay, sand, and animal and vegetable matter. Vicat described loam as the substance found at mouths of rivers, whose tributaries slow over beds of clay or sand, and deposit vegetable debris and animal matters. These matters then mix with the clay and sand, forming the end product, loam. Loam is considered to be a class of sand. (Chambers; Vicat)

Lord Normanby's Cement: See Atkinson's cement.

Lord Stanhope's Cement: Charles, third Earl of Stanhope, invented his cement in the early 1800s. It consisted of Stockholm tar, pulverized chalk, and sand. John Nash used this cement on the roof of Buckingham Palace and on several roofs of houses on Regent

Street, London. It never became popular because in hot weather it tended to melt. (Francis)

Loriot's Cement: Invented by Antoine J. Loriot (1716 - 1782) in the early eighteenth century, it was a mix containing by volume 196 parts of siliceous sand, 196 parts of pulverized calcareous stone, 1 part by weight (of stone and sand's combined weight) of litharge, and 2 parts (of mix's total weight) of linseed oil. Oddly enough, this recipe exactly matches that given for La Rochelle mastic. As many authors from this period discussed Loriot's cement, it is safe to assume that the city engineers at La Rochelle, France "borrowed" Loriot's recipe and renamed it. (Davey)

Lower Chalk: See Gray chalk.

Low-heat Portland Cement: It is similar to ordinary Portland cement, except that it generates less heat during hardening and is more useful for large mass concrete. (Handisyde)

Louisville Cement: A cement produced from cement rock quarried at Louisville, Kentucky. It is like Rosendale cement, but contain less magnesia. In existence at least since 1796, its use declined considerably in the twentieth century and is rare today. See Rosendale cement. (Dancaster; Graham)

Lump Lime: Also known as quicklime and fat lime, it is chiefly composed of calcium oxide or a mix of calcium oxide and magnesia. One source listed some disadvantages for its use: it requires slaking; its quality varies; it spoils if not used soon after it is mixed; and it can not be stored or otherwise kept due to its caustic properties. Hydrated lime was given as an alternative having none of these disadvantages. The same author stated that a few advantages given for fat lime were that it could be prepared in large amounts and that walls could be built faster and easier than with cement. See Fat lime and Quicklime. (Searle; Williams)

Mack's Cement: Dehydrated gypsum with 0.4% of calcined sodium sulphate or potassium sulphate added. Unusually hard, durable, but expensive, it unites minutely with the building material, sets rapidly, is slightly porous, and absorbs very little once it has set hard. (Dancaster; Eckel; Graham)

Magnesia Cement: Also known as "oxychloride cement," it is made from magnesium oxychloride. Calcined magnesia is mixed with a solution of magnesium chloride at 25 or 30^{o} Baume; one mix is 1 part of magnesium chloride, 1 part of magnesia, and 2 parts of water. If the magnesia is prepared from magnesite, it contains little residual carbon dioxide and, though it will set rapidly and give a strong cement, it is liable to develop cracks during setting. If made from magnesium chloride, the magnesia is free from carbon dioxide and, though it will set and harden less rapidly, no cracks will appear. This cement has good binding qualities and is plastic and cheap. (Eckel)

Magnesian Limestone: Also known as "dolomite," the stone is of the Permian formation. Its name is confined to those stones which contain 5 - 35% of magnesium carbonate. (Dancaster)

Mailtre's Cement: It was similar to "mastic de limaille" made from iron filings, garlic, and vinegar. However, sulphuric acid was substituted for the vinegar and it was diluted with water in the proportion of 1 ounce of sulphuric acid to 2 pints of water. Mailtre rejected the garlic as useless. The cement was used to joint stones over terraces, and worked by the oxidation of the iron filings. (Repertory of Arts)

Maltha: Pliny, the Elder said mastic was prepared from fresh lime, the lumps of which were quenched in wine, then pounded or triturated with hogs' lard and figs. It was extremely adhesive and when set was harder than stone. After application, he suggested that the surface be rubbed with oil. In 1703, Joseph Moxon published his treatise, Mechanic Exercises, and described maltha as a mortar made from bitumen found in Rome. He quoted Pliny in suggesting that maltha was good for cisterns, fish ponds, or plastering fronts to represent stone. (Bailey; Bostock; Moxon)

Marble Cements: See Gypsum cements.

Marble Meal: Marble dust ground as fine as meal and the dust then used for fine work. Sir Christopher Wren (1632 - 1723) mentioned marble meal in his 1750 book, Parentalia, recording it as an "old, but still modern" material used in stucco in Italy. It was used by Wren in the stucco of St. Paul's Cathedral in London. (Feilden, "Care of St. Paul"; Hodgson)

Martin's Cement: Patented by Richard Freen Martin (b.? - d.?) of Lambeth in 1834, it resembles Keene's cement, except that the alum used in the latter is replaced by potassium carbonate. It sets rapidly and hard, is durable, and like others of its kind (e.g. Keene's or Mack's cement), is expensive. Vicat stated that it was prepared by calcining bricks composed of powdered gypsum, pearl ash, and the solution of sulphate of potash. (The latter was prepared by neutralising the alkali with an acid.) After calcination in a red heat, the bricks were pulverized. Vicat added that the cement set in two hours to a pure white material and proved not to be injured by frost. (Audley; Dancaster; Francis; Vicat)

Masonry Cement: Suitable for masonry, brickwork, rendering, and plastering, it consists of a mixture of ordinary Portland cement with a very fine mineral filler and an air-entraining agent. Its purpose is to provide a cement more workable than ordinary Portland cement and give a more plastic mortar. Some masonry cements are mixtures of Portland cement with hydrated lime, crushed limestone, diatomaceous earth, or granulated slag with or without small additions of calcium stearate, petroleum, and highly colloidal clays. (ASTM C-219; Handisyde; Lea)

Mason's Putty: Nicholson defined it as a mix of 3 parts of stonedust to 1 part of fat lime. A recipe dating from the 1930s states that the putty consisted of 7 parts of stone dust, 5 parts of Blue Lias lime (now unobtainable), and 2 parts of Portland cement. It is used mainly for close-jointed ashlar masonry. (Bowyer, Handbook; Nicholson; Shore)

Mastic: In general, it refers to cements whose hardness depends on oily or mucilaginous substances within their composition. Formerly, mastic was used extensively for various purposes for which Portland cement is now chiefly employed. It is still used occasionally for pointing joints between the wood frames of windows and masonry. Mastic is waterproof, heat-resistant, and adheres to stone, brick, metal, and glass with great tenacity. Its use dates back to the Roman times, but more recent examples are Scotch mastic, Hamelin's mastic, and Dihl's mastic. Pliny called it "maltha." (Builder's Dictionary; Hodgson; Lomax)

Mastic Cement: It is made from a mix of 60 parts of slaked lime, 35 parts of fine sand, and 3 parts of litharge. The materials are kneaded into a stiff mass with 7 to 10 parts of old linseed oil. Then, the whole mass is beaten and thoroughly mixed until plastic. The cement assumes a fine smooth surface by trowelling. It is impervious to damp and is not affected by atmospheric changes. (Hodgson)

Mastic de Dhil: See Dihl's mastic.

Mastic de Limaille: A mastic composed of iron filings, garlic, and vinegar. See Mailtre's cement. (Repertory of Arts)

McMurtrie Stone: Equal to the best limestones, this artificial stone, dating from the late nineteenth century, has a water absorption two times that of granite. One ingredient is Portland cement, whose pores contain compounds of alumina with fatty acids by the double decomposition of alum and potash soap. It is insoluble in water, is not affected by carbonic acid, and has early strength. (Baker, Treatise)

Meagre Limes: The name given to limes which had the property of hardening in water. Bernard Forest de Belidor (1693 - 1761) called them "beton." See Hydraulic lime or Beton. (Belidor; Payne)

Medina Cement: The original Medina cement was thought to be a variety of Roman cement which was made from a stone found on the Isle of Wight, particularly in the River Medina. Septaria nodules were the main component, but when this source ran out, manufacturers had to resort to the artificial blending of clays and finely ground chalk. A mix of 3 - 4 parts of clay to 2 parts of chalk was used. (Dancaster; Davey; Francis)

Metallic Cement: Nicholas Troughton, an employee of Benson, Logan & Co., copper smelters of Swansea, patented this cement in the 1830s. It was composed of pulverized copper slag and Blue Lias lime. Sir Robert Smirke used it as a stucco on many of the buildings he designed in London. In 1843, The Builder advertised it as a cement made from lime mixed with metallic sand or powder, coarse or fine as required. They stated that hardness increased with dampness as the moisture caused the metallic particles to oxidize and lock themselves together. A mix of 1:1:6 lime:sand:gravel was recommended for use as concrete. Metallic cement remained popular through the 1850s, but declined in use after Smirke discovered that it cracked and peeled off buildings after only two years. (The Builder; Francis)

Milk of Lime: The suspension of hydrated lime or slaked quicklime in water in such proportions as to produce a substance resembling milk. (ASTM C-51)

Minion: A calcined iron ore obtained from the outside of nodules of stone after roasting them. Smeaton thought it to be "a good succedaneum" for pozzolana or trass. He also said that a "Mr. Mitchell" thought minion was what fell from the outside of the iron stone and thus contained more clay. (Burnell; Smeaton, Eddystone Lighthouse)

Mix: The proportions of a batch of mortar or cement.

Modulus of Elasticity (also termed 'Young's modulus'): The ratio of stress to strain, which is constant until the stress reaches the yield point.

Moderately Hydraulic Limes: The third of five classifications for limes, or the first of three classes of hydraulic limes. Burnell stated that all limes containing 8 - 12% of silex, alumina, iron oxides, and magnesia were included in this category. They set under water after 15 - 20 days immersion, continue to harden up to the sixth or eighth month, and are known to dissolve with difficulty in pure water. See Lime. (Burnell; Dancaster; Vicat)

Mortar: An initially plastic material used in masonry to provide even bedding and jointing. Like limes and cements, mortar can be categorized according to their components. Some sources divided mortar into three classes: common or lime mortar which is made with lime; trass or pozzolanic mortar, in which trass or some other pozzolanic material is mixed with lime; and cement mortar, which is made with Portland, natural, or slag cement. Occasionally a fourth category is added: cement-lime mortar, meaning that both lime and cement are found in the mortar. Until recently, authors named mortars according to the mix. For example, lime-cement mortar was a lime mortar tempered with Portland cement, while a cement-lime mortar was strictly a mix of 1:1:6 cement:lime:sand. A cement mortar was cement tempered with lime, while a lime mortar was a mix of 1:4 lime:sand. To add to the confusion, another author defined lime mortar as a mix varying from 1:2-1/2 to 1:5, 1:3 being prefered. If rich limes were used, the lime mortar mix became 1:3-1/2 or a 1:4. The 1913 Sears guide defined mortar as a mix of 1:3 - 3-1/2 lime:sharp river sand, or 1:2:1 lime:sand:blacksmith's ashes. Today the three (or four) types of mortar define only their ingredients, and mixes are left to the ASTM or the BS standards. For example, BRE Digest #160 gives three useful charts suggesting certain mortar mixes for certain types of jobs and areas of use. (Note: In early works on the subject of mortar, it should be remembered that 'mortar' and 'cement' were often used interchangeably.) See Cement. (Baker, Treatise; Dancaster; Graham; Hodgson; Searle; Shertzer; Williams)

Mountain Limestone: See Carboniferous limestone.

Mud Mortar: See Adobe.

Mulgrave Cement: See Atkinson's cement.

Natural Cements: Formed by calcining a naturally occurring mix of calcareous and argillaceous substances at a temperature below that at which sintering occurs. The first two natural cements, "Plaster cement" and "Parker's Patent cement," were produced in 1796 in France and England respectively. Louisville cement and Rosendale cement from America both date from around this time, but the American natural cement industry itself did not gain popularity until 1818. Their popularity remained high until about 1850 when they were replaced slowly by Portland cement. Roman cement and "American Rock" cement are early examples of natural cements. See Louisville cement, Parker's cement, and Rosendale cement. (ASTM C-219; Cowan; Lea)

Neve's Cold Cement: The name of a specific recipe printed by Richard Neve in his 1703 treatise, The City and Country Purchaser. "Take half a Pound of old Cheshire cheese, pare off the Rhind, and throw it away; cut or grate the Cheese very small and put it into a Pot; put to it about a pint of Cows-milk, let it stand all Night, the next Morning get the Whites of 12 or 14 Eggs, then take a Pound of the best slak'd or Quick-lime that you can get, and beat it to

Powder in a Mortar, then sift it through a fine Hair sive, into a Tray or Bowl of Wood, or into an Earthen-dish, to which put the Cheese and Milk, and stir them well together with a Trowel, or such like thing, breaking the Knots of Cheese, if there be any, then add the Whites of the Eggs, and temper all well together, and so use it. The Cement will be of a white Colour; but if you would have it of the Colour of the Brick, put into it either some very fine Brickdust, or Almegram, not too much, but only just to colour it." (Neve)

Neve's Hot Cement: Another of Richard Neve's special recipes printed in his 1703 treatise. "Take one Pound of Rozin, a quarter of a pound of Beeswax, half a ounce of fine Brick-dust, half a Ounce of Chalk-dust, or powder of Chalk; sift both the Brick-dust and Chalk-dust through a fine Hair-sieve (you may beat the Brick, and the Chalk in a Mortar, before you sift it) boil all together in a Pipkin, or other Vessel, about a quarter of an Hour, stirring it all the while with an Iron or a piece of Lath, or such like; then take it off, and let it stand 4 or 5 minutes, and it is fit for Use." (Neve)

New Cement: Invented by a Colonel Maceroni around 1843, it was made from egg whites and oystershell lime. Maceroni stated that the cement could be altered to become a marine cement simply by using shellac as a base. (The Builder)

New Process Lime: The name given to hydrated lime which was processed under a "new process," an invention dating from the early twentieth century. Lumps of quicklime were ground to a fine powder, thoroughly slaked with water and then passed through fine sieves or air separators. The end product was a uniform, fine powder of slaked lime. The main innovation was in the slaking method. Lime simply sprinkled with water was not always thoroughly saturated, but the "new process" was designed to ensure complete saturation with water. (Dancaster)

Nodules: See Septaria. (Davey)

Non-hydraulic: A term used to describe all limes that contain no significant amounts of clay and do not set under water or indurate. Some examples are fat lime, rich limes, poor limes, and lean limes. See Lime. (Williams)

Oil Cements: See Oil Mastics.

Oil Mastics: Oil mastics or cements became popular in the eighteenth century and were also called "oleagineous cements." The mixes and proportions varied, but oil mastics usually contained linseed oil, litharge, and lime. The first probably was patented by Alexander

Emerton (b.? - d.?) about 1737 and consisted of powdered glass, sand, and stone-dust. Wark's cement patented in 1763 and 1765 by the Rev. David Wark was another early oil cement, made from "oils of tar, turpentine and linseed with stone-dust, marble and drift sand, pipe and potters clay, brick dust, brown sugar, lime and various calcareous earths." Another oil cement was patented in 1772 by Charles Rawlinson of Lostwithiel and contained 66 lbs. of whiting, 12 lbs. of sifted sea-coal, 10 lbs. of sifted brick dust, 6 lbs. of white lead, 6 lbs. of red lead, and 17 lbs. of raw linseed oil. Liardet's cement, John's cement, Adam's cement, and Hamelin's cement were other popular examples. The words 'cement' and 'mastic' were interchangeable in the late 1700s. In 1778, John Johnson, an architect from London, was taken to court by the Adam brothers for infringement of Liardet's patent. Johnson (b.? - d.?) patented a cement in March 1777 very similar to Liardet's, except that 'serum of blood' was added to the ingredients. Adams' counsel argued that Johnson included blood in his specification merely to make his cement appear different and on several occasions, he left out the blood altogether. A verdict was issued in favor of the Adam brothers. See Oleaginous cements. (Davey; Francis)

Oil Mastic Stucco: See Wark's cement.

Oleaginous Cements: In London, the cements were usually just called "mastics." Their very fine, close-grained, even surfaces and their ability to retain their beauty over long periods made them popular for use in ornamental decoration. They became obsolete due to their expense and difficult workability, and were replaced by natural or artificial hydraulic cements, especially Portland cement. See Oil mastics. (Dancaster)

Oolitic Limestone: Part of the Jurassic system, oolitic limestone beds do not produce good cementing materials when they are burnt. In England between the marls of Kimmeridge and the clays of Oxford, however, hydraulic oolitic limes once existed which were durable and good, once burnt. Nodules of argillaceous limestone from that area were used in the manufacture of natural cement. (Dancaster)

Opus Caementicium: Roman concrete used to set undressed stones called "caementa." It consisted of lime, sand, and often pozzolana. (Cowan; McKay)

Opus Signinum: Roman concrete consisting of mortar with potsherds or broken bricks added. (Cowan)

Ordinary Portland Cement: A powder made by crushing clinker; adding water produces a hard and fast set. The raw materials used in the manufacture of this cement are limestone or chalk plus an aluminous material, usually clay, together producing hydraulic calcium silicates. Small additions of gypsum or calcium sulfate are used to control the setting properties. The materials are mixed together, usually in the form of a wet slurry, and burned at high temperatures in a rotary kiln to emerge in the form of hard nodules termed clinkers. These are crushed and ground down to a very fine powder. The fineness of grinding is important, since it influences the rate of strength development. The entire process is hard to control and quality varies from one manufacturer to another. See Portland cement. (ASTM C-11; Handisyde; Williams)

Oxychloride Cements: In 1853, the chemist, Sorel (b.? - d.?), discovered that zinc chloride mixed with zinc oxide united to form a very hard cement. Later, it was discovered that the same results occurred when magnesium chloride and magnesia were mixed. The products were similar: an oxychloride of zinc or magnesium. They are also known as Sorel cements. (Eckel)

Parian Cement: A cement prepared in the same manner as Keene's cement, except a solution of borax or the borate of soda is employed in place of alum. It is manufactured by burning a mix of powdered gypsum and dry borax at 600° C. The product is ground into a fine powder and upon application, it sets hard and rapidly and is durable, but like other cements of its kind, is expensive. (Burnell; Dancaster; Sayre)

Paris Mastic: An oil mastic used by military engineers in France, in lieu of La Rochelle mastic used by civil engineers. It consisted of 12 parts by weight of natural or artificial hydraulic cement, 2 parts of white lead, 2 parts of litharge, 6 parts of linseed oil, and 1 part of a richer oil like animal oil. Burnt clay often was used as an artificial cement, and pozzolana, in the same quantities, occasionally replaced the white lead. (Burnell; Dancaster)

Parker's Cement: Originally known as "Parker's Patent Cement" and later renamed "Roman cement," it was invented and patented by Rev. James Parker (b.? - d.?) in 1796 (British Patent #2120-1796). The cement was made by burning calcareous clay nodules from the Essex coast. Vicat said that it consisted of 45% of clay and 55% of carbonate of lime. Equal quantities of the cement and sharp, clean, grit sand mixed together formed a very hard and durable cover for the outsides of edifices. If the sand was wet or damp, the cement was to be used immediately. As a natural cement, it replaced mastics and artificial cements. However, when the patent lapsed in 1810, the cement market was soon flooded with similar cements. By 1850, Roman cement had been replaced almost totally by Portland cement. (Bowyer, Handbook; Melville; Vicat)

Parker's Patent Cement: See Parker's cement.

Parker's Stucco Cement: This cement was a more liquid form of "Parker's cement" and was used by John Nash (1752 - 1835) as a stucco on cheap brickwork to imitate Bath stone. (Hudson, Fashionable Stone; Melville)

Pasley's Cement: Invented by Major-General Pasley and patented in 1824, it was a synthetic hydraulic cement containing burnt chalk and clay. (Hudson, Building Materials)

Patent Lithic Cement: The name given to one of the three Portland cements on the market by 1847. It was manufactured by Messrs Evans and Nicholson in Manchester and consisted of the same ingredients and the same proportions as its two competitors. The other two were Frost's New cement and Blue Lias cement. (Davis, One Hundred Years)

Pebble Dash: See Rough cast.

Pebble Mortar: Another name for "backing mortar," it is used to back rubble walls. An eighteenth century recipe by a "Mr. Nickall" defined the mix as 1:2 common lime:screened pebbles. Smeaton used this recipe, but added an additional 1 part of minion. A building dictionary of 1734 described the mortar as a mix of 4:1:2:2:8 slaked argillaceous lime:terrass:coarse sand:fine sand:small pebbles. (Builder's Dictionary; Lomax; Smeaton, Eddystone Lighthouse)

Peperino: Volcanic stone or tufa from the Alban Hills, southeast of Rome. (McKay)

Pew's Cement: An 1880 mix comprised of 1 part of quicklime to 2 parts of baked clay, and 1 part of gypsum to 2 parts of baked clay. The first two ingredients were mixed and the last two components then added to produce a very hard and durable cement. (Spon)

Pietra Cotta Cement: Just one of many compositions or cements patented prior to the advent of Parker's Roman cement. (Spackman, Calcareous Cements)

Pipe Clay: Fine, white, nearly pure kaolin or china clay. (Chambers)

Pisé: An ancient building material usually confined to arid regions, it is made in several ways. The most common method is to take earth or loam, form it into bricks and dry it in the sun. However, lumps of clay mixed with straw have been used. Pise is a substitute for a mortar of lime and sand. It was introduced in Britain by Henry Holland. (Chambers; Clifton-Taylor; Spackman, Some Writers)

Pisé de Craie: A mortar made of 3:1 chalk:sand, mixed and then rammed tightly down between the shuttering of timber or basketwork. It was popular in Wiltshire, England in the nineteenth century. (Hinde)

Pisé de Terre: It is identical in proportions and application to pise de craie, except the chalk is replaced by clay. (Hinde)

Pit Sand: See Drift sand.

Plaster Cement: An invention of G.L. La Sage (or Lesage) (1724? - 1803?) in 1796 and 1802, it was made from nodules found at Boulogne-sur-mer, France. Like other French natural cements, it was prepared in the same way as Roman cement, except it had lower specific gravity. The cement was ground under edge-runners and passed through an 18 mesh/cm. wire sieve. Similar French cements were prepared by Lacordaire (b.? - d.?) at Pouilly in 1829 and by Gariel (b.? - d.?) at Vassy in 1831. (Dancaster)

Plaster of Paris: Also known as gypsum plaster. A plaster prepared from pure gypsum by converting it into a partially dehydrated compound of calcium sulfate hemihydrate $[2(CaSO_4).H_2O]$. Other varieties are made from impure raw materials or by adding a retarder during or after its manufacture. The impure plasters set slower. (Dancaster; Sayre)

Plastic Deformation: Any deformation of a material under load, which is not recovered when the load is removed.

Plastic Stone: The meaning of this term changed over the years. Originally it referred to a lime and hair mortar that was secured with iron nails. In the nineteenth century, it was the name given to "Roman cement" by such men as Nash. Today, it describes a mortar containing cement with crushed stone and sand, and occasionally, an organic binder such as silicone ester or cellulose acetate is added. (Melville)

Plastic Strain: The strain, caused by an applied stress, that is not recovered when the stress is removed.

Plastre de Corf: A calcined gypsum found in the south of England. Occasionally, it is used as a building mortar, but it is never quite as good as calcined calcium carbonate of lime. 'Plastre de Nower' is another name for gypsum from the south. (Andrews)

Plastre de Nower: See Plastre de Corf.

Poor Lime: It is the second of five classes of lime. See Lean lime and Lime. (Burnell; Dancaster; Vicat)

Portland Blast-furnace Cement: Its manufacture is the same as that for normal Portland cement, except the clinker is mixed with up to 65% of blast-furnace slag for the final grinding process. Its early strength is less than that of ordinary Portland cement, but becomes the same after 28 days. It is more resistant to dilute acids and some other destructive agents, but requires a longer curing period due to its slower rate of strength gain. (Handisyde; Lea)

Portland Cement: "Roman cement" by Parker and "Aspdin's Portland cement" were the forerunners of this product. The first reliable Portland cement was created by I.C. Johnson at Swanscombe, Kent, England in 1845. Portland cement was first manufactured in France in 1853; in Germany (at Stettin) in 1855, and in America (Coplay, Pennsylvania) in 1872. It was, however, first introduced in America in 1865. In the twentieth century, the name was shortened to 'cement' as all other cements had more or less become obsolete. At the same time, the confusion over 'cement' and 'mortar' ceased, 'cement' referring strictly to Portland cement unless otherwise noted. Technology has created a variety of Portland cements, produced by slightly altering the ordinary Portland cement ingredients. Some examples of this are: rapid hardening Portland cement; extra rapid hardening Portland cement; white and colored Portland cement; Portland blast-furnace cement; low-heat Portland cement; water-repellent Portland cement; and waterproof Portland cement. (For further details on these variations, see the specific cement.) The one popular cement mortar mix is 1:3 Portland cement:sand, however many authors use other mixes based on the job required: 1:1/2:4; 1:1/2:5; 1:1:6, or 1:2:8 Portland cement:lime:sand. Nicholson suggested that these mixes be used because they produced suitable building mortars. Portland cement was given its name by Aspdin who thought it looked like Portland stone. See Aspdin's Portland cement, Lime-cement mortars, and Ordinary Portland cement. (Bowyer, <u>Handbook</u>; Davis, <u>Portland Cement</u>; Handisyde; Hudson, <u>Building Material</u>; Nicholson; Radford; Skempton)

Portland-pozzolana Cement: A hydraulic cement made by adding 20% of pozzolana to Portland cement, so as to combine with its free lime and reduce its liability to leach or to increase its fire resistance. It hardens slower than ordinary Portland cement, but reaches the same final strength. If more than 40% of pozzolana is used, then it is described as a pozzolana cement. (ASTM C-219; Scott, <u>Civil Engineering</u>)

Portland Stone: A natural oolitic limestone quarried at Portland, England. Occasionally, it was the name given to an artificial stone made from a mix of 1:2 - 2-1/2 Portland cement:sand, sometimes with additional gravel. (Baker, <u>Treatise</u>)

Pozzolana: It is a naturally occurring substance consisting of silica, ash, alumina, lime, magnesia, iron oxides and alkalies. Also called "pulvis puteolanus," pozzolana is a volcanic tufa or ash of the best variety from the neighborhood of Pozzoli, Italy, but later was extended to encompass the whole class of mineral matters of which this is one type. Pumice, Santorin earth, and trass are other mineral matters with similar properties. In the presence of moisture, pozzolana chemically reacts with calcium hydroxide to form a compound possessing cementitious properties. It was a popular ancient building material and its use was discussed by Vitruvius and Smeaton. The most frequently quoted formulae are 1:2-1/2 lime:pozzolana; 1:2 lime:trass; or 1:1:1 lime:sand:pozzolana or trass. Pozzolana, when incorporated into a mix, gives mortar the ability to set in damp conditions. (Graham; Lea; Smeaton, Diary; Vitruvius; Williams)

Pozzolana Cement: Also called "pozzolanic cement," it is a mix of pure lime and hydrated silica, but the latter is very expensive. Some mixes recommend the use of Kieselguhr, a natural, active silica, but this also is expensive. Vicat stated that this cement contained 70 - 90% of clay and 30 - 10% of lime. Pozzolana cement also includes artificial hydraulic limes, prepared by mixing slaked limes with natural or artificial burnt siliceous matter. (Audley; Davey; Vicat)

Pozzolanic Mortars: The second of three categories for mortar. This class includes all mortars in which trass or some other pozzolanic material is mixed with lime. See Mortar. (Dancaster)

Psammities' Sand: This sand is an assemblage of grains of quartz, slate, feldspar, and mica. (Vicat)

Pulverized Fuel Ash: Also termed 'pulverized fly ash' and abbreviated 'PFA,' it is the ash of pulverized coal used in power stations. (Williams)

Pumice: Trachytic lava found on the shores of the Tyrrhenian Sea and on the Island of Lipari. In general, it refers to a hardened froth of glassy lavas, full of minute gas-cavities and hence, able to float in water. (Chambers; Hurst)

Purified Lime: The finer and richer part of the lime able to pass through a sieve. (Nicholson)

Quarry Sand: See Drift sand.

Quicklime: Known as fresh, unslaked lime, it is an unstable material produced when limestone is burnt, and water and carbon dioxide are driven off. The main constituent is calcium oxide or magnesium oxide, both of which slake on the addition of water. (ASTM C-11; Shertzer; Williams)

Ranger's Artificial Stone: Patented by William Ranger (b.? - d.?) of Brighton on June 4, 1833, it was made from 30 lbs. of silicious matter, 3 lbs. of pure lime, and 3 gallons, 12 ounces of boiled water. The ingredients were mixed and then sprinkled with iron sulphate. Or, stone with iron in it such as Blue Lias could be used in lieu of the above materials. Ranger preferred stone lime from Dorking and washed sea or river sand, or flints or copper slag. The materials were placed in a mould until hardened. Due to its adverse affects by frost and water, it became unpopular by 1840. (Francis; Repertory of Arts)

Ransome Stone: Invented by Fredrick Ransome (b.? - d.?), it is an artificial stone formed by the natural decomposition of two unnamed chemical compounds in a solution. When the chemical solution was mixed with sand, gravel, or pulverized stone, it became a hard and insoluble cementing substance. (Baker, Treatise; Land and Building News)

Rapid Hardening Portland Cement: The manufacturing process is similar to that of ordinary Portland cement, however the chief difference lies in the degree of fineness to which the clinker is ground. Such fineness results in an increased rate of strength gain, but not in a quicker setting time. (Handisyde)

Rawlinson's Cement: See Oil mastics.

Rendering Cement: A tough cement plaster replacing lime and hair mortar in plastering walls. (Sturgis)

Rich Lime: See Fat lime.

Rich Sand: A powder produced from the disaggregation and decomposition of rocks. (Vicat)

Rhone Mortar: A mortar consisting of pure lime and certain argillaceous or loamy sands called "arenes." (Spackman, Some Writers)

Roach Lime: A rare name for calcined lime, the term was used in an Irish treatise by George Semple (1700 - 1782). He recommended a mix of 1:4:8 roach lime:sand:stone as a suitable mortar. (Davey; Semple; Singer)

Robinson's Cement: The 1913 Sears guide said that this cement had fire-resisting qualities and was suitable for use in concrete. It was cheaper than other cements like it, but no mention was made of its components. (Hodgson)

Rock Stones: Another name for septaria. See Septaria. (Davey)

Roman Cement: 'Roman cement' was the most popular name for "Parker's cement;" however in Great Britain, it also was called "water cement." Later, the name came to include all naturally hydraulic cement containing a high percentage of clay materials. Patented in 1796, Parker's cement was prepared by calcining nodules of septaria from London clay. The brown color of the cement was thought to resemble the appearance of Roman mortar, so Parker renamed it "Roman cement." The name is misleading, though, for in no way did it resemble Roman mortar. Although it was used principally as a rendering material, it was used in pointing in the nineteenth century, especially in the restoration and repair of joints. (Lea; Vicat; Williams)

Roman Mortar: The Romans made mortar using lime and sand, or pozzolana and sand. Vitruvius spoke of these, using mix ratios of 1:2 - 3 lime or pozzolana:sand. Also, a hard, durable and waterproof mortar made of lime and hogs' grease, then mixed with the juice of figs. Or, it was a mix of lime with liquid pitch, wet or slaked with wine, then pounded with hogs' grease and the juice of figs. Upon application, the mortar was washed over with linseed oil. (Builder's Dictionary; Vitruvius)

Rosendale Cement: Made from argillaceous magnesian limestone of the Appalachian Mountain range in the United States, it was very similar in composition and application to Roman cement. It contained 15 - 18% of magnesia, 2 - 4% of alumina, and 18 - 25% of silica. Dating from about 1796, it was discontinued in the mid-twentieth century. See Louisville cement. (Dancaster)

Rough Cast: Also known as "wet dash" or "pebble dash," it is a durable, coarse external rendering. Usually two coats of cement and sand are applied on to which gravel, crushed stone, shingle, spar, broken bricks, glass, pottery, or pebbles are thrown before the second coat is dry. (Hodgson; Pevsner)

Rough Stucco: Used to imitate stone, this stucco is worked with a hand float covered with a rough cloth to raise the sand and produce a stone-like appearance. (Hodgson)

St. Leger's Patent: A process patented in 1818 (British Patent #4262-1818), it was an "improved" method of making lime out of a fat or pure carbonate of lime by adding clay or any substance containing alumina and silex. The recommended mix consisted of 1 to 20 measures of clay or other similar substance to every 100 measures of chalk, stone or lime. (Spackman, Calcareous Cements)

Saltpeter: Also spelled "saltpetre," it is more commonly known as "efflorescence" and is potassium nitrate (KNO_3), a product of sodium nitrate and potassium chloride. (Burnell)

Sand: A fine aggregate usually referred to by a specific name such as beach sand, pit sand, arenes, fine sand, coarse sand, or quarry sand. It is found in streams, beds, or pits in the earth, and on seashores, and for building purposes, should be siliceous, gritty, not too fine, perfectly clean, and free from organic matter. Sands formed by trituration of finely grained or amorphous rock, and fine pebbles are used for mortar. Sand was divided into seven categories by Vicat: clean: sand with a small amount of fine grains; dirty: sand with too much silt, clay, or organic contamination; sharp: sand with coarse, harsh, angular grains; soft: sand with mostly fine and clayey content; clayey: sand with a lot of fines, mostly clay; loamy: sand with a lot of organic matter, such as humus from soil; and washed: sand from which salt or other impurities have been washed out. British Standards and ASTM have described soils in the following manner, based on size:

Description	British Standard	ASTM
coarse sand	2.0 to 0.6 mm	2.0 to 0.25 mm
medium sand	0.6 to 0.2 mm	----
fine sand	0.2 to 0.06 mm	0.25 to 0.05 mm
coarse silt	0.06 to 0.02 mm	
medium silt	0.02 to 0.006 mm	0.05 to 0.005 mm
fine silt	0.006 to 0.002 mm	
clay	under 0.002 mm	under 0.005 mm

(ASTM C-125; BS 1377; Scott, Civil Engineering; Vitruvius)

Santorin Earth: A volcanic deposit or tufa from the Island of Thera (now Santorin), it produces a light gray-colored ash. It is employed by the Greeks in building to achieve superior strength and to resist the action from water. The earth is ground and mixed with lime and sand. (Dancaster; Lea)

Scagliola: An ornamental plasterwork of gypsum and glue made to imitate granite or marble. The best scagliola contains a large number of small pieces or splinters of marble. These splinters or "scaglioli" give it its name. It is made by a repeated process of rubbing and polishing. (Dancaster)

Scorched: Rich lime which slakes to dryness and loses its workability. (Vicat)

Scoriae: The lighter, more porous, and less perfectly vitrified slags which arise from the puddling and refining of iron. It also refers to less compact portions of slag. (Burnell)

Scotch Mastic: A mastic composed of 14 parts of white or yellow sandstone, 3 parts of whiting, and 1 part of litharge. First, the sandstone was pounded or ground to a fine powder. Then, all the ingredient were mixed on a hot plate to expel any moisture and sifted to remove coarse particles. Finally, the mass was gauged with raw and boiled linseed oil in the proportion of 2 parts of raw oil to 1 part of boiled oil. Before application, the surface to be covered was brushed with linseed oil. (Hodgson)

Scott's Cement: Also known as "selenitic cement," it was patented in March, 1854 (British Patent #735-1854) by Colonel Henry Young Darracott Scott (b.? - d.?). The cement was manufactured by a process whereby sulphur combined with feebly hydraulic lime to form calcium sulphite ($CaSO_3$), and then was oxidized to calcium sulphate ($CaSO_4$). Once ground to an impalpable powder, it was stored until ready for use. One source disputed the use of feebly hydraulic lime and stated that it was quicklime with 5% of plaster of Paris. Nevertheless, Scott claimed the end product was better than hydraulic lime, but was not suited for work exposed to weather or salt water. The more popular Portland cement eventually ousted it from the market. (Dancaster; Francis; Graham)

Selenitic Cement: See Scott's cement.

Septaria: Also known as "rock stones" or "cement stones," it is nodules of argillaceous limestone found in certain tertiary strata or clay beds along the foreshore of the Thames Estuary and elsewhere. Septaria was used in 1796 by James Parker in manufacturing his Roman cement. Later, Nicholson defined septaria as the clay balls in "Roman cement" stones. It was derived from "septa of carbonate of lime" and could be called "ludus helmontii" which was 60% of lime, 8 - 10% of iron protoxide, and the rest, silex and alumina. (Davey; Lea; Nicholson)

Setting: The first hardening of mortar. A mortar paste initially displays plasticity, but after a period of time begins to stiffen until all plasticity is gone. The paste becomes brittle, although it is still without any sizeable strength. This stiffening process is called setting and is marked by the period of change in the mortar-water mixture during which the reactions are accelerating. (Popovics; Scott, Building)

Setting Stuff: Used for the finish coat in lime plastering, it is a material composed of lime putty and washed, fine sharp sand. The proportion of sand varies according to the class of lime and the type of work, but the average is 3 parts of sand to 1 part of putty. It is less liable to shrink and crack if it is allowed to stand until nearly hard, but not dry. Then, it should be knocked up to the required consistency with water, preferably lime water. (Hodgson)

Sewage Cement: This cement was the product of a process developed by H.Y.D. Scott, inventor of Scott's cement, in about 1870. It was manufactured by Scott's Sewage Co. Ltd. and a pamphlet issued by the firm in 1873 states that 1 - 1-1/2 tons of quicklime were used for the treatment of 1 million gallons of sewage water. One ton of quicklime produced 30 tons of wet sludge and 3 tons of dry sludge. The dry material was burned, resulting in 1-1/2 tons of cement. (Francis)

Shear: A state of stress in which the material is subject to opposite stresses not in the same line of action, and in which one plane tends to slide across an adjacent plane.

Sheppy Cement: A cement made from 32% of clay and 66% of lime. (The Builder; Vicat)

Short: In mixing mortar, the mix becomes "too short" if the quantity of aggregate is relatively high. This means the mortar is not sufficiently plastic and workable, and may crumble shortly after application. (Arch. Pub. Soc., Dictionary)

Shrinkage: See Drying Shrinkage.

Sidero Cement: Invented by Frederick Krupp (1854 - 1902), this cement was analyzed and discovered to consist of 23.26% of silica, 1.67% of alumina, 8.20% of ferric oxide, 64.84% of lime, 0.6% of magnesia, and 1.08% of sulphur trioxide for a total of 99.71%. It was similar to Portland cement, except the rich alumina clays usually used were replaced by iron ores, manganese ores, or chrome ore tailings. The materials were mixed with chalk marl or silica. (Dancaster; Spackman, Calcareous Cements)

Silex: Another name for silica. (Burnell; Cooley)

Silica Mortar: A mortar composed of 1 part of silica flour and 1 part of clean coarse silica sand. (Shore)

Silt: Granular materials finer than sand, but coarser than clay: between 0.002 to 0.06 mm in size. (Scott, Civil Engineering)

Simply Energetic: The second of four classes which Vicat used to define various materials' reaction with lime. See Lime. (Vicat)

Sinter: It is obtained by burning hydraulic limes at very high temperatures, causing the lime to coalesce into a single mass without liquefying. (Chambers)

Slag: The waste glass-like product from a metallurgical furnace, which flows off above the metal. Burnell originally defined slag as vitrified earths left in furnaces after purer products have been removed. (Burnell; Scott, Civil Engineering)

Slag Cement: Also called "cold process slag cement," this cement is a mixture of hydrated lime and granulated blast-furnace slag. The slag is obtained from iron smelting operations and formed into a cement by combining it with limestone and ore. Certain salts may be added to accelerate the set. (ASTM C-219; Dancaster; Lea)

Slaked Lime: See Hydrated lime.

Slaking: The hydration of quicklime, formed by combining calcium oxide and water. (Scott, Building)

Slightly Energetic: The third of four classes which Vicat used to define various materials' reaction with lime. See Lime. (Vicat)

Slime: In Biblical times, it was an alternate word for bitumen. See "Genesis" in The Bible. (Sturgis)

Sorel Cement: See Oxychloride cement.

Staff Plaster: See Fibrous plaster.

Stone Lime: A fresh lime which produces the most heat in slaking and slakes the quickest. Nicholson said stone lime could be identified by dissolving it in distilled vinegar. It would produce the least effervescence and leave the smallest residue to clay and gypsum. It also is the name given to lime produced from gray chalk and occasionally, is called "flare lime." See Gray chalk. (Dancaster; Nicholson)

Stone-lime Mortar: The 1913 Sears guide defined it as a mix of 1:2 - 3 gray lime:sand. (Hodgson)

Stonemasons' Cement: An 1880 cement made from a mix of 20 lbs. of clean river sand, 2 lbs. of litharge, 1 lbs. of quicklime, and linseed oil. Made into a thin paste, it was used to unite stone fragments and became exceedingly hard and strong once dry. (Spon)

Strain: A measure of the deformation of a member caused by an applied stress, calculated by dividing the change of length at a given time by the original length.

Strain Ratio: The ratio of maximum strain (instantaneous and creep) to instantaneous strain.

Stress: The force in a member divided by the area which carries the force, expressed in N/mm^2.

Stucco: It is a form of plastering which is worked to resemble stone such as marble, and generally is made from a base of lime mixed with calcareous powder or chalk. However, Nicholson said that stucco was called "lime setting stuff," and consisted of 3 parts of lime putty to 2 parts of fine, washed sand. It originated in Italy where it was used as a superior external and an occasional internal plaster. In England, the external use of stucco to give brick houses the appearance of stone is due to Robert Adam. Roman cement and selenitic lime were two popular products used to stucco building fronts during the first half of the nineteenth century. By 1850, these materials were superseded by Portland cement. Stucco's plastic nature enables it to adapt itself to most architectural purposes with very considerable decorative effects. However, Portland cement and the use of stone and terra cotta have decreased the use of external stucco. In the United States, stucco has become an indefinite term, used loosely for various plastic mixtures made from lime, plaster, or cements. For internal walls, stucco is called "trowelled" or "bastard" stucco, and is composed of a mix of 3:1 fine stuff:very fine washed sand. See specific names of stucco. (Bowyer, Handbook; Burnell; Hodgson; Nicholson)

Stucco-duro: Also known as "hard stucco," it was used in the 1400s in Italy and consisted of old air-slaked lime and marble dust, occasionally with fine sand and hair added. Burnt gypsum could be added to give it a better set. (Davey)

Sulphation: A term used to describe the irregular crystalline skin formed by the reaction of sulphur gases in the atmosphere with limestone or lime mortar, and ultimately causing decay. See Saltpeter. (Williams)

Super Cement: Dating from approximately 1910, the cement was stronger and more waterproof than ordinary Portland cement. It was made of normal Portland cement with some unidentified material added to render it waterproof, thus alleviating the need to entrust the mixing of the waterproofing compound to workmen. Its increased strength was the main difference from the usual waterproofing materials which tended to weaken the cement with which they were used. (Dancaster)

Super-sulphated Cement: A cement resistant to the sulphates found in ground water and soils, and, resistant to peaty acids and vegetable oils. (Handisyde)

Tabby: A cement made of lime, sand, or gravel, and shells such as oyster and used chiefly along the coast of Georgia and South Carolina in the seventeenth and eighteenth century. (Webster)

Terras: See Trass.

Tarrace: An ancient mortar composed of lumps of lime, wet or slaked with wine, then pounded with hogs' grease and pitch. This recipe is very similar to that given for "Roman mortar." (Moxon)

Tarras Mortar or Terras Mortar: Also spelled "trass," it is the name of one of the mortars used by Smeaton on the Eddystone lighthouse. He found this mortar being made on the banks of the River Scheldt during a visit to Holland in 1755. One layer of hydraulic lime or blue argillaceous lime was spread on the ground, one foot thick. After moistening with water, it was covered with a one foot thick layer of trass and allowed to set for two days. Then, the materials were thoroughly mixed together and beaten. After setting for another two days, the mortar was ready to use. Nicholson in his treatise, The Practical Builder (1848), defined this mortar as a mix of 2:1:0, 2:1:1, 2:1:2, or 2:1:3 lime:terras:sand; however a cheaper version was 1:2:3. Contrary to this 1848 book, an earlier work, The Builder's Dictionary (1734), defined terras mortar differently. Trass or "wakke" was mixed with blue argillaceous lime, then sprinkled with water and covered with terras. After two days, it was beaten and covered for two more days. See Trass. (Builder's Dictionary; Davey; Lomax; Nicholson; Smeaton, Diary)

Tension: A state of stress in which the particles of a material tend to be pulled apart, thus tending to elongate it.

Terra Cotta: Fired clay, glazed or unglazed, used mainly for wall coverings and ornamentation, since it can be fired in moulds. See Artificial stone. (Pevsner)

Terrass Stone: Called "dough stone" or "trass" in Holland, it comes to that country from German mines where it is dug in the manner of coal. The only preparation required is to reduce it to a powder. It is a hard material, but has a very spongy texture. (Smeaton, Diary)

Tetin: A reddish pozzolana found in the Azores Islands. (Dancaster)

Thenard's Unchangeable Cement: See Litharge mastic.

Timchent: A local gray gypsum plaster used in stucco and rubble walls at Sedrate, 500 miles south of Algiers in the Sahara, in the tenth through thirteenth centuries. (Davey)

Tophus: The ancient and Latin name for travertino. See Travertino. (The Builder)

Tosca: Used mainly in Spain, it is a pozzolana found in Teneriffe in the Canary Islands. (Dancaster)

Trass: Occasionally spelled "terrass," "tarass," "tarras," or "terras," the accepted spelling today is "trass." Originally from Germany, it was specifically from the Eifel district between Bonn and Anderach by the Rhine. This district produced a trass which was a pale yellow or gray, metamorphosed, volcanic ash. It was also the name given to similar materials obtained from Holland and France. Trass contains less lime than pozzolana, but more silica. See Tarras mortar. (Dancaster; Graham)

Trass Mortar: The correct way to spell Smeaton's "tarras mortar" or Nicholson's "terras mortar." It is the second of three categories used to define mortar. See Mortar.

Travertine: See Travertino.

Travertino: Also called "calc-sinter," "tufa," or "tuff." Originally called "tophus," it is a stone in Italy or a volcanic tufa. However, it differs from pozzolana and other volcanic tufas in that it is a variety of limestone deposited by calcareous springs. Travertino possesses the valuable property of hardening on exposure to air. See Tufa. (ASTM C-119; Land and Building News)

Trowelled Stucco: Used as a finish coat for internal work, this stucco is made from a mix of 1:2 sand:fine stuff, and is worked with a hand float until a fine, smooth surface is produced. (Hodgson)

Tufa: A soft stone composed of volcanic matter concreted together by heat. Found in Italy, particularly Rome, it was easily quarried. Peperino was considered a stronger version of tufa, and travertino a stronger version yet. In England, the name, tufa, was given to any light, porous stone, not necessarily of volcanic origin. (Arch. Pub. Soc., Dictionary)

Tuff: See Tufa.

Turkish Luting or Cement: A mortar composed of 100 lbs. of picked kilned lime, 10 qts. of linseed oil, and 1 - 2 ounces of cotton. It was stored in dried cakes; when ready for use it was moistened with linseed oil. (Land and Building News)

Upper Chalk: See White chalk.

Vassey Cement: Invented by Gariel in 1831, it was a French natural cement, very dark in color on account of a large quantity of iron. The cement's set was quickest when used immediately after having been freshly burned. Similar in nature to "Plaster cement" prepared by Le Sage and another prepared by Lacordaire at Pouilly, Vassey cement got its name from the town in which it was invented. See Plaster cement. (Dancaster)

Vauban's Mastic: This cement was used for lining cisterns. The recipe called for 5 - 6 parts by volume of rich lime mixed with linseed oil. Then, 2 parts of good cement which had been passed through a fine sieve were added. The mix was beaten for one half day and laid aside overnight. For one half hour the next day, it was beaten again and then applied. After three to four days, the second through fourth coats were applied to the surface. (Dancaster)

Very Energetic: The first of four categories created by Vicat for the purpose of classifying various materials' reactions with lime. See Lime. (Vicat)

Victoria Cement: A pozzolanic cement made from a mix of 3 parts of finely ground slag, previously granulated by running in water, and 1 part of slaked lime by weight. If kept moist, the mix set slowly and became hard and strong. (Graham)

Wakke: Also known as "cellular basalt," it was the name Nicholson used for trass. (Lomax)

Wark's Cement: An oil mastic or stucco created by Rev. David Wark DD (b.? - d.?). It consisted of tar oils, turpentine, linseed oil, stone-dust, marble and drift sand, clay, brick dust, brown sugar, and lime, and was first patented in 1763. Another patent was issued on June 27, 1765 in Haddington, East Lothian, Scotland. Robert Adam bought this patent to use as his own as he did with the Liardet's cement patent. See Oil mastics. (Cruikshank; Davey; Francis; Hudson, <u>Building Materials</u>)

Water Cement: Many authors of treatises in the late eighteenth through nineteenth centuries used this name when referring to Roman cement. (Smeaton, <u>Eddystone Lighthouse</u>; Vicat)

Water Lime: Another name for hydraulic lime, it was used by Smeaton and other English engineers. (Burnell)

Waterproof Portland Cement: Ordinary Portland cement with waterproofing ingredients such as calcium, aluminum or other metal stearate, or non-saponifiable oil added. Concrete made with this type of cement has more resistence to water and oil penetration than concrete made from ordinary Portland cement. (Handisyde; Lea)

Water-repellent Portland Cement: Also called "hydrophobic cement," it is ordinary Portland cement with stearates mixed in and is mainly used in rendering to check moisture penetration. If used in concrete, care should be taken to avoid any reduction in strength. (Handisyde; Scott, <u>Civil Engineering</u>)

Water table: Known as a watershed or offshoot in Britain, it is a board or masonry projection fixed to the foot of a wall to shoot water away from it. Also, a contrasting course of masonry near the base of a wall. (Scott, <u>Building</u>)

Whitby Cement: A cement made from the Whitby shale beds of the Lias formation in Yorkshire, England. (Davey)

White Cements: The 1913 Sears guide stated that these cements had a tendency to shrink, according to the stiffness of the gauge. However, no ingredients or proportions for white cement were given. (Hodgson)

White Chalk: Also called 'upper chalk,' it is the purest of the common forms of calcium carbonate found in the Cretaceous system, it contains from 1 - 6% of clay, sand, magnesia, iron oxide, and other impurities. Lime produced from this stone is termed "fat" or "rich" lime, and is the only suitable materials for air mortars. It is a popular component of Portland cement. (Dancaster)

White Mortar: Used by Jean R. Perronet (1708 - 1794), the mix consisted of 1 part of Vernon lime and 3 parts of sharp clean sand from the River Seine. In foundations exposed to water, the mix was altered to 1:2 lime:artificial pozzolana. Originally, the mortar was used for plastering walls and ceilings. First, a loam plaster was applied, followed by a white mortar mix of 1 part by volume of hair (either ox or cow), and 6 parts of lime. The lime was tempered with the hair and water, and no sand was required. (Builder's Dictionary; Neve; Spackman, Some Writers)

White Portland Cement: A white cement made from much purer raw materials than those used for ordinary Portland cement. China clay is used in the mix as a substitute for the usual materials, which contain iron oxides. (Dancaster; Handisyde)

Whiting: Pure chalk ground in water and run through a fine-meshed sieve. (Arch. Pub. Soc., Dictionary)

Williams's Patent Mortar, or Stucco: Patented by Dr. Richard Williams (b.? - d.?) on December 11, 1780 (British Patent #1272-1780), it was composed of a mix of 12 lbs. of pure lime, 10 lbs. of water, 84 lbs. of pure coarse sand, and 4 lbs. of grated skimmed-milk cheese. (The Builder)

Yield Point: The stress at which a material starts deforming rapidly in a clearly plastic fashion.

Yorkshire Cement: See Atkinson's cement.

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Rector, Mark. Project Manager, May Construction Company, Brighton, Massachusetts. Interview, June 1981.

Robertson, Angus. T. Harley, Haddow, Engineers, Edinburgh, Scotland. Telephone interview, November 11, 1982 and February 22, 1984.

Salewski, Dr. Structural Engineer, Massachusetts Institute of Technology, Cambridge, Massachusetts. Interview, March 6, 1984.

Smith, W. Superintendent, Scottish Development Department, Edinburgh, Scotland. Interview, February 26, 1981.

Technical advisors. Rohm & Haas Company, North Jersey, New Jersey. Telephone interview, February 15, 1984.

Weiss, Norman. Assistant Professor, Columbia University, New York, New York. Interview, April 15, 1981.

Appendix 3: Equipment and Material Sources

Air Conditioner (Qualitair, Model 160H):
Manufacturer: Qualitair Ltd.
Kent, England
Supplier: John E. Bastow Ltd.
West Silvermills Lane
Edinburgh, Scotland
Property of: Department of Architecture
University of Edinburgh
20 Chambers Street
Edinburgh, Scotland EH1 1JZ

Analytical Balance (Mettler digital scale, Model PC4400):
Manufacturer: Mettler Instrument AG
Zurich, Switzerland
Supplier: A. Gallenkamp & Co., Ltd.
Braeview Place, Nerston
East Kilbride, Scotland
Property of: Department of Architecture
University of Edinburgh

Cube Moulds (for 100 mm specimens, as per BS 1881:1970):
Supplier(?): Wykeham Farrance Ltd.
Weston Road, Trading Estate,
Slough, Berks.
England S11 4HW
Property of: Department of Architecture
University of Edinburgh

Cylinder Moulds (McAlpine Waste High Density Pipe, HD3 white 2"):
Manufacturer: McAlpine Ltd.
Glasgow, Scotland
Supplier: UBM Scotland Ltd.
39 Albert Street
Edinburgh, Scotland EH7 5LP

Demec Strain Gauge (Model 2551):
Manufacturer: W.H. Mayes & Son
Windsor, Berks., England
Supplier: W.H. Mayes & Son
Property of: Simpson & Brown, Architects
179 Canongate
Edinburgh, Scotland EH8 8BN

Dropping Ball Apparatus (as per BS 4551):
Supplier(?): Wykeham Farrance Ltd.
Weston Road, Trading Estate,
Slough, Berks.
England SL1 4HW
Property of: Building Department

Heriot-Watt University
Chambers Street
Edinburgh, Scotland

Humidifier (Defensor, Model 505):

Manufacturer:	Defensor Aktiengesellschaft Zurich, Switzerland
Supplier:	John E. Bastow Ltd. West Silvermills Land Edinburgh, Scotland
Property of:	Department of Architecture University of Edinburgh

Hydraulic Testing Machine (Avery Denison, Model T.42.B.4, max. 500 kN):

Manufacturer:	Avery Denison Ltd. Leeds, England
Property of:	Building Department Heriot-Watt University Chambers Street Edinburgh, Scotland

Oedometer (Rear-loading):

Manufacturer:	Workshop, Department of Architecture University of Edinburgh
Property of:	Department of Architecture University of Edinburgh

Sieves (Mesh sizes, aperture in mm: 2.36, 1.18, 0.6, 0.3, 0.15) (as per BS 410:1969):

Supplier:	Wykeham Farrance Ltd. Weston Road, Trading Estate Slough, Berks. England SL1 4HW
Property of:	Department of Architecture University of Edinburgh

Thermohygrograph (Spring-powered with bimetallic and hair elements):

Manufacturer:	Casella Ltd. London, England
Supplier(?):	Griffin & George Ltd. 285 Ealing Road Alperton, Wembley, Middlesex England HA0 1HJ
Property of:	Department of Architecture University of Edinburgh

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Builders' Sand:	Manufacturer:	William Stokes & Co., Ltd. Dolphinton, Scotland
	Supplier:	The Builders' Supply Co., Ltd. 495 Gorgie Road Edinburgh, Scotland EH11 3AS

Coarse Stucco (CB stucco as per BS 1191):
Manufacturer: British Gypsum Ltd.
Kirby, Scotland
Supplier: The Builders' Supply Co., Ltd.
495 Gorgie Road
Edinburgh, Scotland EH11 3AS

De-ionised Water: Supplier: Anderson, Gibb & Wilson Ltd.
543 Gorgie Road
Edinburgh, Scotland EH11 3AR

Hydrated Lime ('Limbux'):
Manufacturer: Imperial Chemical Industries, PLC
Buxton, Derbyshire, England
Supplier: The Builders' Supply Co., Ltd.
495 Gorgie Road
Edinburgh, Scotland EH11 3AS

Hydraulic Lime (Chaux De Paviers, Eminement Hydraulique XHN):
Manufacturer: Paviers
Crouzilles, France
Supplier: Edinburgh New Town Conservation Committee
The City of Edinburgh District Council
Dundas Street
Edinburgh, Scotland

Portland Cement (Ordinary)
Manufacturer: Blue Circle Industries Ltd.
Dunbar, Scotland
Supplier: The Builders' Supply Co., Ltd.
495 Gorgie Road
Edinburgh, Scotland EH11 3AS

Rendaplas (Alkaline, double strength mortar plasticiser admixture, Vinsol Resin based on air entraining agents):
Manufacturer: Cementone Ltd.
Buckingham., England
Supplier: Compliments of:
Rowebb Ltd.
2 Ronaldson's Wharf, Leith,
Edinburgh, Scotland EH6

Appendix 4: Completed Survey Form

MORTAR SURVEY
Background Information

Address: 2781 Parkard Road
Ann Arbor, Michigan
Country: U.S.A.

IDENTIFICATION

Original Owner: Dr. Benajah Ticknor
Present Owner & Address: City of Ann Arbor, Michigan

Original Building Name: Ticknor House
Present Building Name: Cobblestone Farm/Ticknor-Campbell House

General Topography/Zoning/Direction: house faces south; is part of Buhr Park; surrounding park are large housing developments on soft rolling land; Packard Road is 4 lanes wide.
Original Use: residence
Current Use: residence/working farm museum

Date of Construction: stone portion: 1844
Dates of Alterations (describe): kitchen, pantry, milkhouse, hired men's dorm, toilets, woodshed added in 1845; more barns in 1860s.
Architect(s): Stephen Mills, mason
Style: Federal with Italianate front porch (portions removed)
Size/Bays/Storeys: 5 bays; 2 storeys
Building Materials: fieldstone quoins; cobblestones; lime mortar; wood porch
Original Mortar Components: burnt limestone from nearby lime pit; local coarse sand
Original Mortar Proportions: 1:7-9
Source of Information: 1) Mrs. Nan P. Hodges, C.F.A., 2940 Fuller Rd., Ann Arbor, Michigan 48105; 2) Olaf Shelgren, Cary Lattin, and Robert Frasch, Cobblestone Landmarks of New York State (Syracuse: Syracuse University Press, 1978).

RESTORATION 1

Architect(s):
Supervisor:
Date Work Undertaken: pre-1972 By: George Campbell
Type of Repair Work: Bedding: X Repointing: X
Location of Repairs: stonework on the front of the house near the south-east corner.
Specification Requirements for Mortar: none

New Mortar Components: premixed formula of lime and portland cement; sand from gravel pit behind house
New Mortar Proportions: 1:3
Thickness of Joint: 1-2 cm Uniformity: yes

REMARKS

Date:	By:	Case Study No.	Sheet No.
25 May 1981	Lauren-Brook Sickels	19	19-1

MORTAR SURVEY
Further Restoration Information

Address: 2781 Parkard Road
Ann Arbor, Michigan
Country: U.S.A.

RESTORATION/REPAIR NO. 2

Architect(s): City of Ann Arbor
Supervisor:
Date Work Undertaken: 1973 By: City of Ann Arbor
Type of Repair Work: Bedding: Repointing: yes, cracks only
Location of Repairs: east end of the stone house, southwest corner around dark fieldstone quoin
Specification Requirements for Mortar:
New Mortar Components: ordinary ready mix mortar
New Mortar Proportions:
Tickness of Joint: less than 1 cm Uniformity: no

RESTORATION/REPAIR NO. 3

Architect(s): Richard Neumann, 604 Bay, Petoskey, Michigan 49770
Supervisor: Cobblestone Farm Association
Date Work Undertaken: 1979 By: Roy Gerow, stone mason
Type of Repair Work: Bedding: X Repointing: X
Location of Repairs: stonework above back door
Specification Requirements for Mortar:
New Mortar Components: masonry mortar mix; mason's sand
New Mortar Proportions: 1:3
Thickness of Joint: varys Uniformity: no

FURTHER REMARKS

Date:	By:	Case Study No.	Sheet No.
25 May 1981	Lauren-Brook Sickels	19	19-2

MORTAR SURVEY Performance Information	Address: 2781 Packard Road Ann Arbor, Michigan Country: U.S.A.

DETERIORATION

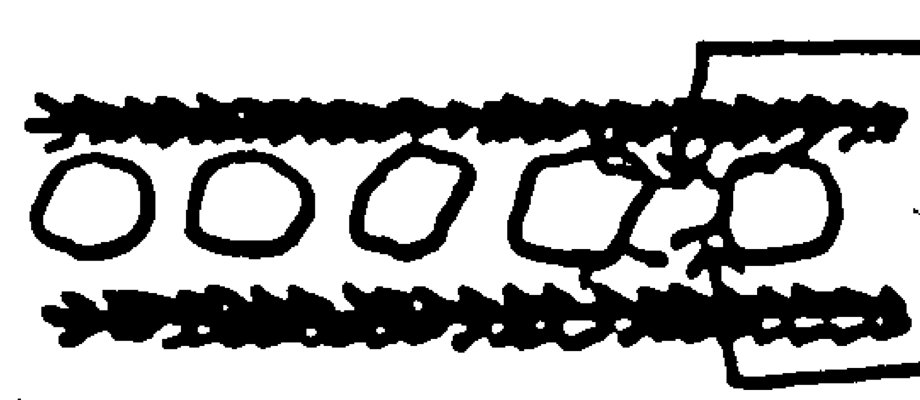
Age of Repair at Time of Observation: minimum 9 years: pre-1972 repair

Problem:	Yes	No	Location on Building Material:	Size:	Source/Cause:
Cracking:	X		around one stone	minute	workmanship
Crazing:		X			
Spalling:		X			
Efflorescence:		X			
Staining:		X			
Coheson of New to Old:	X				
Bond of Joint Itself:	X				
Pigmented:					
Aggregate:	X				
Inorganic:		X			
Uniformly colored:		X			
Other:					

DIAGRAMS OF DAMAGE

Diagrams of Damage (not to scale)

see Figure __



ENVIRONMENT As Applied to Building Exposure

General Area Weather Statistics: summers: 80-90 F, very humid; winters: 20 F with high wind chill factor, 3" of snow with blowing storms

Specific Site Topography: flat land, well-shaded and cared for.

Effects from:

Wind: stone is sheltered by large bush

Water:

Rain: very little on south wall

Rising Damp:

Other:

Sun: none

Frost:

Ground:

Biological Sources:

Other:

REMARKS

This repair lacks the quality of the originally-worked joints. The color is different, but the old-to-new joints appear good. Some attempt was made to recreate the herringbone pattern.

Date:	By:	Case Study No.:	Sheet No.:
25.5.81	Lauren-Brook Sickels	19	19-3

MORTAR SURVEY
Performance Information

Address: 2781 Packard Road
Ann Arbor, Michigan

Country: U.S.A.

DETERIORATION

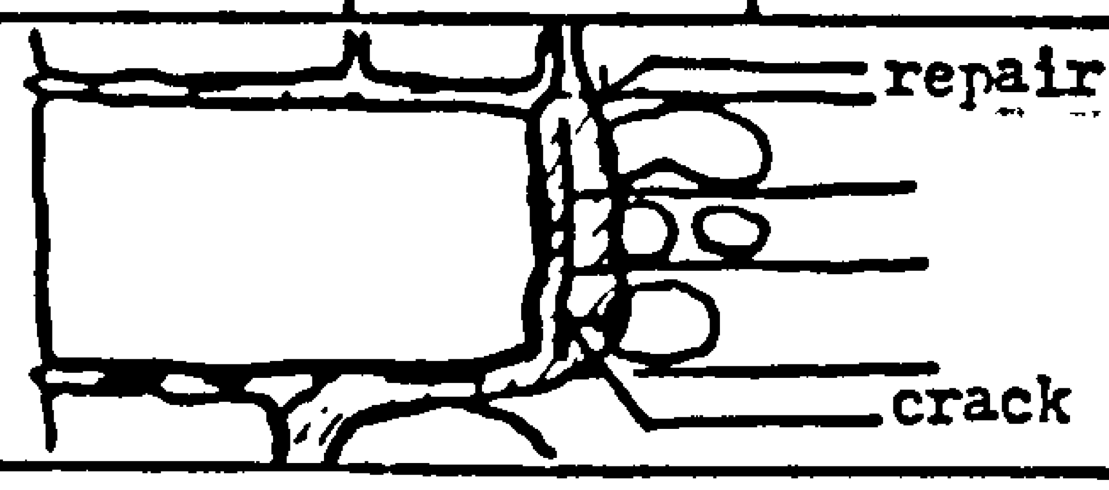
Age of Repair at Time of Observation: 8 years: 1973

Problem:	Yes	No	Location on Building Material:	Size:	Source/Cause:
Cracking:	X		middle of repair around lg. crack	length of quoin	old crack
Crazing:	X			minute	
Spalling:		X			
Efflorescence:		X			
Staining:		X			
Coheson of New to Old:	X				
Bond of Joint Itself:		X	east side of quoin		previous crack reopening
Pigmented:					
Aggregate:	X				
Inorganic:		X			
Uniformly colored:	X				
Other:					

DIAGRAMS OF DAMAGE

Diagrams of Damage
(not to scale)

see Figure __



ENVIRONMENT
As Applied to Building Exposure

General Area Weather Statistics:

Specific Site Topography:

Effects from:
Wind:
Water:
Rain:
Rising Damp:
Other:
Sun:
Frost:
Ground:
Biological Sources:
Other:

REMARKS

Portland cement has blue-gray color and is darker than the warm-colored original mortar.

Date:	By:	Case Study No.:	Sheet No.:
25.5.81	Lauren-Brook Sickels	19	19-4

MORTAR SURVEY Performance Information	Address: 2781 Packard Road, Ann Arbor, Michigan Country: USA

DETERIORATION

Age of Repair at Time of Observation: 2 years: 1979

Problem:	Yes	No	Location on Building Material:	Size:	Source/Cause:
Cracking:		X			
Crazing:		X			
Spalling:		X			
Efflorescence:		X			
Staining:		X			
Coheson of New to Old:	X				
Bond of Joint Itself:	X				
Pigmented:					
Aggregate:	X				
Inorganic:		X			
Uniformly colored:	X				
Other:					

DIAGRAMS OF DAMAGE

Diagrams of Damage (not to scale)

ENVIRONMENT - As Applied to Building Exposure

General Area Weather Statistics:

Specific Site Topography:

Effects from:
- Wind:
- Water:
  - Rain:
  - Rising Damp:
  - Other:
- Sun:
- Frost:
- Ground:
- Biological Sources:
- Other:

REMARKS

No damage apparent. However, color of new does not match the old and due to random arrangement of stones on this north or back wall, mortar is all over. It is applied in a sloppy manner and is around the edges of several stones.

Date:	By:	Case Study No.:	Sheet No.:
25.5.81	Lauren-Brook Sickels	19	19-5

Appendix 5: Sample of Creep and Shrinkage Data

H.P.

Samples 1:2:9 H Cyl. 1-4
Controls 5-10

26.77 kg   13.75 kg

Date	1 Fig	1 Diff	2 Fig	2 Diff	3 Fig	3 Diff	4 Fig	4 Diff	5 Fig	5 Diff	6 Fig	6 Diff	7 Fig	7 Diff	8 Fig	8 Diff	9 Fig	9 Diff	10 Fig	10 Diff
2.25.30^b 2/13							6.69	0.00	6.65	0.00	7.06	0.00	6.88	0.00	7.21	0.00	7.00	0.00	7.01	0.00
2:26.00^a							6.58	0.11												
2:26.30							6.57	0.12												
2:27							6.57	0.12 = Ei												
2:28							6.56	0.13												
2:31							6.55	0.14												
2:28.15^b					7.00	0.00														
2:28.45^a					6.845	0.155														
2:29.15					6.82	0.18														
29.45					6.82	0.18 = Ei														
2:30.45					6.82	0.18														
2:33.45					6.815	0.185														
2:41							6.55	0.14												
2:43.45					6.80	0.20														
2:31^b			7.14	0.00																
2:31.30^a			6.89	0.25																
2:32			6.86	0.28																
2:32.30			6.855	0.285 = Ei																
2:33.30			6.84	0.30																
2:36.30			6.83	0.31																
2:46.30			6.81	0.33																
2:35^b	6.845	0.00																		
2:35.30^a	6.275	0.57																		
2:36.30	6.22	0.625 = Ei																		
2:37.30	6.20	0.645																		
2:40.30	6.16	0.685																		
2:50.30	6.10	0.745																		
2:56							6.525	0.165												
2:58.45					6.785	0.215														
[illegible] 01			6.78	0.36																
[illegible] 05 30	6.035	0.81																		
[illegible] 26 30							6.51	0.18												
[illegible] 28.45					6.765	0.235														
[illegible] 31 30			6.75	0.39																
[illegible] 35.30	5.985	0.86																		
[illegible] 56							6.50	0.19												
[illegible] 58 45					6.745	0.255														
[illegible] 1 30			6.72	0.42																
4. [illegible]5.30	5.94	0.905																		
4:[illegible].30							6.475	0.215												

Date	Aver 1+2	Aver 3+4	Aver 5-10	Aver (1+2)-(5-10)	Aver (3+4)-(5-10)	Creep 1	Creep 2	Creep 3	Creep 4	Aver Creep 1+2	Aver Creep 3+4
2.25.30^b 2/13			0.00						0.00		
2:26.00^a											
2:26.30											
2:27									0.00		
2:28									0.01		
2:31									0.02		
2:28.15^b		0.00			0.00			0.00			0.00
2:28.45^a		0.1325			0.1325						
2:29.15		0.15			0.15						
29.45		0.15			0.15			0.00			0.00
2:30.45		0.155			0.155			0.00			0.005
2:33.45		0.1625			0.1625			0.005			0.0125
2:41									0.02		
2:43.45		0.17			0.17			0.02			0.02
2:31^b							0.00				
2:31.30^a											
2:32											
2:32.30							0.00				
2:33.30							0.015				
2:36.30							0.025				
2:46.30							0.045				
2:35^b	0.00			0.00		0.00				~~0.00~~	
2:35.30^a	0.41			0.41							
2:36.30	0.455			0.455		0.00				0.00	
2:37.30	0.4725			0.4725		0.02				0.0175	
2:40.30	0.4975			0.4975		0.06				0.0425	
2:50.30	0.5375			0.5375		0.12				0.0825	
2:56									0.045		
2:58.45		0.19			0.19			0.035			0.04
[illegible] 01							0.075				
[illegible] 05 30	0.585			0.585		0.185				0.13	
[illegible] 26 30									0.06		
[illegible] 28.45		0.2075			0.2075			0.055			0.0575
[illegible] 31 30							0.105				
[illegible] 35.30	0.625			0.625		0.235				0.17	
[illegible] 56									0.07		
[illegible] 58 45		0.2225			0.2225			0.075			0.0725
[illegible] 1 30							0.135				
4. [illegible]5.30	0.6625			0.6625		0.28				0.2075	
4:[illegible].30									0.095		

-2- -2 2-

Date	1 Fg	1 Diff	2 Fg	2 Diff	3 Fg	3 Diff	4 Fg	4 Diff	5 Fg	5 Diff	6 Fg	6 Diff	7 Fg	7 Diff	8 Fg	8 Diff	9 Fg	9 Diff	10 Fg	10 Diff	Aver 1+2	Aver 3+4	Aver 5-10	Aver (1+2)-(5-10)	Aver (3+4)-(5-10)	Creep 1	Creep 2	Creep 3	Creep 4	Aver Creep 1+2	Aver Creep 3+4
-28.45					6.73	0.27			6.65	0.00	7.06	0.00	6.98	0.00	7.21	0.00	7.00	0.00	7.01	0.00		0.2425			0.2425			0.09			0.0925
4 31.30			6.695	0.445																							0.16	—			
- 35.30	5.90	0.945																			0.695			0.695		0.32		—		0.24	
5:36.30							6.45	0.24																				—	0.12		
5.28.45					6.70	0.30																0.27			0.27			0.12			0.12
5 31.30			6.66	0.48																							0.195	—	—		
5:35.30	5.84	1.005																			0.7425			0.7425		0.38		—	—	0.2875	
?50 22/3	5.34	1.505	6.36	0.78	6.46	0.54	6.23	0.46	6.56	0.09	6.97	0.09	6.90	0.08	7.11	0.10	6.92	0.08	6.935	0.075	1.1425	0.50	0.0858	1.0567	0.4142	0.7742	0.4092	0.2742	0.2542	0.6017	0.2642
10.50 23/3	4.94	1.905	6.09	1.05	6.23	0.77	6.04	0.65	6.45	0.20	6.90	0.16	6.81	0.17	7.01	0.20	6.83	0.17	6.85	0.16	1.4775	0.71	0.106	1.3715	0.604	1.174	0.659	0.484	0.424	0.9165	0.454
2.45 24/3	4.65	2.195	5.87	1.27	6.06	0.94	5.85	0.84	6.35	0.30	6.765	0.295	6.725	0.255	6.91	0.30	6.745	0.255	6.75	0.26	1.7325	0.89	0.2775	1.455	0.6125	1.2925	0.7075	0.4825	0.4425	1.00	0.4625
1.15 25/3	4.415	2.43	5.73	1.41	5.94	1.06	5.74	0.95	6.305	0.345	6.72	0.34	6.67	0.31	6.86	0.35	6.68	0.32	6.725	0.285	1.92	1.005	0.325	1.595	0.68	1.48	0.80	0.555	0.505	1.14	0.53
1.45 28/3	3.84	3.005	5.27	1.87	5.59	1.41	5.39	1.30	6.10	0.55	6.515	0.545	6.49	0.49	6.67	0.54	6.48	0.52	6.54	0.47	2.4375	1.355	0.5192	1.9183	0.8358	1.8608	1.0658	0.7108	0.6608	1.4633	0.6855
2:05 29/3	3.74	3.105	5.18	1.96	5.54	1.46	5.35	1.34	6.075	0.575	6.515	0.545	6.475	0.505	6.67	0.54	6.46	0.54	6.525	0.485	2.5325	1.40	0.5317	2.0008	0.8683	1.9483	1.1433	0.7483	0.6983	1.5458	0.7183
12:00 30/3	3.655	3.19	5.11	2.03	5.48	1.52	5.29	1.40	6.07	0.58	6.495	0.565	6.47	0.51	6.665	0.545	6.45	0.56	6.51	0.50	2.61	1.46	0.5417	2.0683	0.9183	2.0233	1.2033	0.7983	0.7383	1.6133	0.7683
1.40 31/3	3.59	3.255	5.03	2.11	5.43	1.57	5.235	1.455	6.055	0.595	6.47	0.59	6.42	0.56	6.635	0.575	6.44	0.56	6.495	0.515	2.6825	1.5125	0.5658	2.1167	0.9467	2.0442	1.2592	0.8292	0.7692	1.6517	0.7967
2.00 1/4	3.465	3.38	4.955	2.185	5.345	1.655	5.16	1.63	6.03	0.62	6.48	0.58	6.39	0.59	6.61	0.60	6.42	0.58	6.485	0.525	2.7825	1.5925	0.5825	2.20	1.01	2.1725	1.3175	0.8726	0.8275	1.745	0.86
12:00 4/4	3.325	3.52	4.84	2.30	5.31	1.69	5.10	1.59	5.995	0.655	6.42	0.64	6.35	0.63	6.58	0.63	6.395	0.605	6.435	0.575	2.91	1.64	0.6225	2.2875	1.0175	2.2725	1.3925	0.8875	0.8475	1.8325	0.8675
1 35 5/4	3.28	3.565	4.81	2.33	5.27	1.73	5.07	1.62	5.985	0.665	6.42	0.64	6.32	0.66	6.55	0.66	6.35	0.65	6.41	0.60	2.9475	1.675	0.6458	2.3017	1.0292	2.2742	1.3992	0.9042	0.8542	1.8367	0.8792
3:30 6/4	3.23	3.615	4.77	2.37	5.245	1.755	5.04	1.65	5.95	0.70	6.38	0.68	6.305	0.675	6.53	0.68	6.33	0.67	6.40	0.61	2.9925	1.7025	0.6692	2.3233	1.0333	2.3208	1.4158	0.9058	0.8608	1.8683	0.8833
11:15 7/4	3.18	3.665	4.73	2.41	5.205	1.795	5.015	1.675	5.92	0.73	6.36	0.70	6.28	0.70	6.51	0.70	6.31	0.69	6.38	0.63	3.0375	1.735	0.6917	2.3458	1.0433	2.3483	1.4333	0.9233	0.8633	1.8908	0.8933
11:45 8/4	3.16	3.685	4.72	2.42	5.195	1.805	4.995	1.695	5.92	0.73	6.37	0.69	6.27	0.71	6.505	0.705	6.285	0.715	6.38	0.63	3.0525	1.75	0.6967	2.3558	1.0533	2.3633	1.4383	0.9283	0.8783	1.9008	0.9033
10 00 11/4	3.03	3.815	4.61	2.53	5.095	1.905	4.92	1.77	5.86	0.79	6.26	0.80	6.22	0.76	6.45	0.76	6.20	0.80	6.345	0.665	3.1725	1.8375	0.7625	2.41	1.075	2.4275	1.4825	0.9625	0.8875	1.955	0.925
Unload 11/4	3.55	3.295	4.93	2.21	5.235	1.765	5.03	1.66	5.86	0.79	6.26	0.80	6.22	0.76	6.45	0.76	6.20	0.80	6.345	0.665	2.7525	1.7125	0.7629	1.99	0.95	1.9075	1.1625	0.8125	0.7775	1.535	0.80
12.30 "	3.655	3.19	4.995	2.145	5.28	1.72	5.065	1.625	5.86	0.79	6.26	0.80	6.22	0.76	6.45	0.76	6.20	0.80	6.345	0.665	2.6675	1.6725	0.7625	1.905	0.91	1.8025	1.0975	0.7775	0.7425	1.45	0.76
4.15 "	3.69	3.156	5.01	2.13	5.27	1.73	5.06	1.63	5.86	0.79	6.26	0.80	6.22	0.76	6.45	0.76	6.20	0.80	6.345	0.665	2.6925	1.68	0.7625	1.88	0.9175	1.7675	1.0825	0.7875	0.7475	1.425	0.7675
12:00 12/4	3.745	3.10	5.06	2.08	5.30	1.70	5.065	1.605	5.835	0.815	6.28	0.78	6.21	0.77	6.43	0.78	6.195	0.805	6.33	0.68	2.59	1.6525	0.7717	1.8183	0.8808	1.7033	1.0233	0.7483	0.7133	1.3633	0.7308
10 50 14/4	3.815	3.03	5.12	2.02	5.35	1.65	5.12	1.57	5.84	0.81	6.28	0.78	6.21	0.77	6.45	0.76	6.21	0.79	6.325	0.685	2.525	1.61	0.7658	1.7592	0.8492	1.6392	0.9692	0.7092	0.6842	1.3042	0.6942
7:30 15/4	3.815	3.03	5.115	2.025	5.34	1.66	5.10	1.59	5.815	0.835	6.245	0.815	6.18	0.80	6.42	0.79	6.16	0.84	6.30	0.71	2.528	1.625	0.7958	1.7317	0.9267	1.6067	0.9417	0.6917	0.6317	1.2742	0.6767
3:00 2/5	3.92	2.925	5.18	1.96	5.365	1.635	5.145	1.545	5.77	0.88	6.19	0.87	6.145	0.835	6.395	0.815	6.13	0.87	6.26	0.75	2.492	1.59	0.8367	1.6053	0.7533	1.4633	0.8383	0.6183	0.5883	1.1508	0.6033
~~10:00 2/6~~	~~3.905~~		~~5.18~~		~~5.35~~		5.14																								
~~12:00 4/6~~	~~3.72~~		~~5.16~~		~~5.355~~		5.14																								

-3- N.P. -3-

Samples 1:2:9H Cyl. 5+6
Controls 7-10

Date	5 Fig.	5 Diff.	6 Fig.	6 Diff.	7 Fig.	7 Diff.	8 Fig.	8 Diff.	9 Fig.	9 Diff.	10 Fig.	10 Diff.	Aver. 5+6	Aver. 7-10	Aver. (5+6)-(7-10)	Creep 5	Creep 6	Aver. Creep 5+6
9 23 45[b] 23/5			6.16	0.00	6.05	0.00	6.32	0.00	6.06	0.00	6.175	0.00		0.00				
9.24.15[a]			6.08	0.08														
9:24.45			6.07	0.09														
9.25.15			6.06	0.10 *Ei													0.00	
9.26.15			6.06	0.10													0.00	
9:29.15			6.065	0.095													(0.005)	
9.39.15			6.06	0.10													0.00	
9:27. [b]	5.72	0.00											0.00		0.00			
9:27.30[a]	5.675	0.045											0.062		0.062			
9:28	5.65	0.07											0.08		0.08			
9 28.30	5.65	0.07 *Ei											0.085		0.085	0.00		0.00
9 29.30	5.65	0.07											0.085		0.085	0.00		0.00
9.32.30	5.64	0.08											0.087		0.087	(0.01)		0.002
9:42.30	5.63	0.09											0.095		0.095	0.02		0.01
9:54.15			6.06	0.10													0.00	
9.57.30	5.63	0.09											0.095		0.095	0.02		0.01
10·24 15			6.035	0.125													0.025	
10:27.30	5.62	0.10											0.112		0.112	0.03		0.027
10·54.15			6.03	0.13													0.03	
10·57.30	5.615	0.105											0.117		0.117	0.035		0.037
11:24.15			6.01	0.15													0.05	
11.27.30	5.605	0.115											0.132		0.132	0.045		0.047
11:54 15			6.01	0.15													0.05	
11:57.30	5.605	0.115											0.132		0.132	0.045		0.047
12:24.15			6.01	0.15													0.05	
12:27.30	5.605	0.115											0.132		0.132°	0.045		0.047
10·00 24/5	5.59	0.13	6.01	0.15	6.02	0.03	6.29	0.03	6.05	0.01	6.175	0.00	0.14	0.017	0.123	0.043	0.033	0.038
12:30 25/5	5.59	0.13	6.00	0.16	6.05	0.00	6.315	0.005	6.06	0.00	6.165	0.01	0.145°	0.004°	0.141	0.056	0.056	0.056
12:45 26/5	5.56	0.16	5.985	0.175	6.05	0.00	6.315	0.005	6.065	(0.005)	6.175	0.00	0.167	0.00	0.167	0.09	0.075	0.082
1:00 27/5	5.56	0.16	5.97	0.19	6.045	0.005	6.31	0.01	6.05	0.01	6.16	0.015	0.175°	0.01°	0.165	0.08°	0.08°	0.08
12:45 30/5	5.55	0.17	5.965	0.195	6.045	0.005	6.31	0.01	6.055	0.005	6.16	0.015	0.182	0.009	0.173	0.091	0.086	0.089
10:15 31/5	5.53	0.19	5.945	0.215	6.05	0.00	6.32	0.00	6.06	0.00	6.175	0.00	0.202	0.00	0.202	0.12	0.115	0.118
2:15 1/6	5.53	0.19	5.945	0.215	6.05	0.00	6.32	0.00	6.05	0.01	6.17	0.005	0.202	0.004	0.198	0.116	0.111	0.113
11:45 2/6	5.51	0.21	5.945	0.215	6.05	0.00	6.30	0.02	6.055	0.005	6.17	0.005	0.212	0.008	0.204	0.132	0.107	0.119
12:15 3/6	5.505	0.215	5.92	0.24	6.04	0.01	6.31	0.01	6.055	0.005	6.15	0.025	0.228	0.013	0.215	0.132	0.127	0.129
2:15 6/6	5.51	0.21	5.92	0.24	6.04	0.01	6.31	0.01	6.05	0.01	6.15	0.025	0.225	0.014	0.211	0.126	0.126	0.126
11:15 7/6	5.495	0.225	5.92	0.24	6.035	0.015	6.30	0.02	6.05	0.01	6.15	0.025	0.232	0.019	0.213	0.136	0.126	0.131
10:15 8/6	5.46	0.26	5.915	0.245	6.04	0.01	6.30	0.02	6.05	0.01	6.16	0.015	0.252	0.014	0.238	0.176	0.131	0.153
2:00 9/6	5.49	0.23	5.925	0.235	6.055	(0.005)	6.32	0.00	6.065	(0.005)	6.18	(0.005)	0.232	(0.004)	0.236	0.164	0.139	0.151
1:45 10/6	5.45	0.27	5.90	0.26	6.03	0.02	6.30	0.02	6.05	0.01	6.17	0.005	0.265	0.014	0.251	0.186	0.146	0.166

350

-4- N.P. -4-

Samples 1:2:9H Cyl 5-6
Controls 7-10

Date	5		6		7		8		9		10		Aver.		Aver (5+6)-(7-10)	Creep		Aver Creep
	Fig	Diff.	Fig	Diff.	Fig	Diff.	Fig	Diff.	Fig	Diff.	Fig	Diff.	5+6	7-10		5	6	5+6
4:00 12/6	5.44	0.28	5.985	0.275	6.035	0.015	6.30	0.02	6.04	0.02	6.155	0.02	0.278	0.019	0.259	0.191	0.156	0.173
4:01 Reached [illegible]	5.53	0.19	5.985	0.175		0.015							0.182	0.019	0.163	0.101	0.056	0.078
4:38 14/6	5.545	0.175	5.96	0.20		"							0.188	0.019	0.169	0.086	0.081	0.083
4:05 15/6	5.53	0.19	5.94	0.22	6.015	0.035	6.285	0.035	6.02	0.04	6.14	0.035	0.205	0.035	0.17	0.085	0.085	0.085
10:50 14/6	5.54	0.18	5.975	0.185	6.02	0.03	6.275	0.045	6.03	0.03	6.145	0.03	0.182	0.034	0.148	0.076	0.051	0.063
4:15 16/6	5.545	0.175	5.97	0.19	6.005	0.045	6.27	0.05	6.02	0.04	6.13	0.045	0.182	0.045	0.137	0.06	0.045	0.052

NP

Shrinkage 1:2:4H

Date		1 Fig	1 Diff	2 Fig	2 Diff	3 Fig	3 Diff	4 Fig	4 Diff	5 Fig	5 Diff	6 Fig	6 Diff	7 Fig	7 Diff	8 Fig	8 Diff	9 Fig	9 Diff	10 Fig	10 Diff	Aver 1-10
14	7/3																					
15	8/3																					
16	9/3																					
17	10/3																					
18	11/3	8.07	0.00	8.39	0.00	8.29	0.00	7.87	0.00	7.77	0.00	8.23	0.00	8.10	0.00	8.385	0.00	8.145	0.00	8.24	0.00	0.00
19	12/3	8.04	0.03	8.355	0.035	8.265	0.025	7.865	0.005	7.75	0.02	8.21	0.02	8.065	0.035	8.37	0.015	8.12	0.025	8.22	0.02	0.023
20	13/3	7.95	0.12	8.22	0.17	8.14	0.15	7.785	0.085	7.65	0.12	8.09	0.14	7.97	0.13	8.27	0.115	8.00	0.145	8.095	0.145	0.132
21	14/3	7.85	0.22	8.12	0.27	8.045	0.245	7.69	0.18	7.57	0.20	7.99	0.24	7.87	0.23	8.16	0.225	7.92	0.225	8.00	0.24	0.2275
22	15/3	7.71	0.36	7.96	0.43	7.91	0.38	7.57	0.30	7.45	0.32	7.80	0.43	7.755	0.345	8.01	0.375	7.815	0.33	7.865	0.375	0.3645
23	16/3	7.54	0.53	7.82	0.57	7.73	0.56	7.425	0.445	7.275	0.495	7.67	0.56	7.595	0.505	7.855	0.53	7.64	0.505	7.69	0.55	0.525
24	17/3	7.38	0.69	7.665	0.725	7.57	0.72	7.25	0.62	7.135	0.635	7.57	0.66	7.445	0.655	7.715	0.67	7.525	0.62	7.55	0.69	0.6685
25	18/3	7.225	0.845	7.54	0.85	7.435	0.855	7.11	0.76	7.055	0.715	7.40	0.83	7.32	0.78	7.58	0.805	7.39	0.755	7.40	0.84	0.8035
27	20/3	6.97	1.10	7.27	1.12	7.17	1.12	6.855	1.015	6.77	1.00	7.10	1.13	7.075	1.025	7.31	1.075	7.11	1.035	7.12	1.12	1.074
28	21/3	6.845	1.225	7.14	1.25	7.00	1.29	6.69	1.18	6.65	1.12	7.06	1.17	6.98	1.12	7.21	1.175	7.00	1.145	7.01	1.23	1.1905
29	22/3									6.56	1.21	6.97	1.26	6.90	1.20	7.11	1.275	6.92	1.225	6.935	1.305	1.2458
30	23/3									6.45	1.32	6.90	1.33	6.81	1.29	7.01	1.375	6.83	1.315	6.85	1.39	1.3367
31	24/3									6.35	1.42	6.765	1.465	6.725	1.375	6.91	1.475	6.745	1.40	6.75	1.49	1.4375
32	25/3									6.305	1.465	6.72	1.51	6.67	1.43	6.86	1.525	6.68	1.465	6.725	1.515	1.485
35	28/3									6.10	1.67	6.515	1.715	6.49	1.61	6.67	1.715	6.48	1.665	6.54	1.70	1.6792
36	29/3									6.075	1.695	6.515	1.715	6.475	1.625	6.67	1.715	6.46	1.685	6.525	1.715	1.6918
37	30/3									6.07	1.70	6.495	1.735	6.47	1.63	6.665	1.72	6.45	1.695	6.51	1.73	1.7017
38	31/3									6.055	1.715	6.47	1.76	6.42	1.68	6.635	1.75	6.44	1.705	6.495	1.745	1.7258
39	1/4									6.03	1.74	6.48	1.75	6.39	1.71	6.61	1.775	6.42	1.725	6.485	1.755	1.7425
42	4/4									5.995	1.775	6.42	1.81	6.35	1.75	6.58	1.805	6.395	1.75	6.435	1.805	1.7825
43	5/4									5.985	1.785	6.42	1.81	6.32	1.78	6.55	1.835	6.35	1.795	6.41	1.83	1.8058
44	6/4									5.95	1.82	6.38	1.85	6.305	1.795	6.53	1.855	6.33	1.815	6.40	1.84	1.8292
45	7/4									5.92	1.82	6.36	1.87	6.28	1.82	6.51	1.875	6.31	1.835	6.38	1.86	1.8467
46	8/4									6.92	1.82	6.37	1.86	6.27	1.83	6.505	1.88	6.285	1.86	6.38	1.86	1.8517
49	11/4									5.86	1.91	6.26	1.97	6.22	1.88	6.45	1.935	6.20	1.945	6.345	1.895	1.9225
50	12/4									5.835	1.935	6.28	1.95	6.21	1.89	6.43	1.955	6.195	1.95	6.33	1.91	1.9317
51	13/4									5.845	1.925	6.285	1.945	6.215	1.885	6.45	1.935	6.21	1.935	6.34	1.90	1.9208
52	14/4									5.84	1.93	6.28	1.95	6.21	1.89	6.45	1.935	6.21	1.935	6.325	1.915	1.9258
53	15/4									5.815	1.955	6.245	1.985	6.18	1.92	6.42	1.965	6.16	1.985	6.30	1.94	1.9583
57	19/4									5.75	2.02	6.245	1.985	6.13	1.97	6.395	1.99	6.145	2.00	6.28	1.96	1.9875
58	20/4									5.775	1.995	6.24	1.99	6.12	1.98	6.415	1.97	6.145	2.00	6.285	1.955	1.9817
60	22/4									5.78	1.99	6.275	1.955	6.165	1.935	6.41	1.975	6.14	2.005	6.245	1.995	1.9758
63	25/4									5.79	1.98	6.285	1.945	6.17	1.93	6.435	1.95	6.15	1.995	6.25	1.99	1.965
65	27/4									5.80	1.97	6.22	2.01	6.18	1.92	6.41	1.975	6.175	1.97	6.275	1.965	1.9683
70	2/5									5.77	2.00	6.19	2.04	6.145	1.955	6.395	1.99	6.13	2.015	6.26	1.98	1.9967
73	5/5									5.73	2.04	6.19	2.04	6.085	2.015	6.34	[illegible]	6.11	2.035	6.21	2.03	2.031
77	9/5									5.73	2.04	6.15	2.08	6.11	1.99	6.375	2.01	6.125	2.02	6.22	2.02	2.027

-2-

Shrinkage 1:2:9H

Date	5		6		7		8		9		10		aver.
	Fig.	Diff.	Fig.	Diff.	Fig.	Diff.	Fig.	Diff.	Fig.	Diff.	Fig.	Diff.	5-10
80 12/5	5.69	2.08	6.11	2.12	6.075	2.005	6.355	2.03	6.08	2.065	6.175	2.065	2.061
85 17/5	5.69	2.08	6.13	2.10	6.07	2.03	6.33	2.055	6.07	2.075	6.19	2.05	2.065
87 19/5	5.68	2.09	6.11	2.12	6.055	2.045	6.32	2.065	6.06	2.085	6.18	2.06	2.077
90 22/5	5.685	2.085	6.13	2.10	6.06	2.04	6.31	2.075	6.06	2.085	6.17	2.07	2.076
91 23/5					6.05	2.05	6.32	2.065	6.06	2.085	6.175	2.065	2.066
92 24/5					6.02	2.08	6.29	2.095	6.05	2.095	6.175	2.065	2.084
93 25/5					6.05	2.05	6.315	2.07	6.06	2.085	6.165	2.075	2.07.
94 26/5					6.05	2.05	6.315	2.07	6.065	2.08	6.175	2.065	2.066
95 27/5					6.045	2.055	6.31	2.075	6.05	2.095	6.16	2.08	2.076
98 30/5					6.045	2.055	6.31	2.075	6.055	2.09	6.16	2.08	2.075
99 31/5					6.05	2.05	6.32	2.065	6.06	2.085	6.175	2.065	2.066
100 1/6					6.05	2.05	6.32	2.065	6.05	2.095	6.17	2.07	2.07
101 2/6					6.05	2.05	6.30	2.085	6.055	2.09	6.17	2.07	2.07[illegible]
102 3/6					6.04	2.06	6.31	2.075	6.055	2.09	6.15	2.09	2.079
105 6/6					6.04	2.06	6.31	2.075	6.05	2.095	6.15	2.09	2.08
106 7/6					6.035	2.065	6.30	2.085	6.05	2.095	6.15	2.09	2.084
107 8/6					6.04	2.06	6.30	2.085	6.05	2.095	6.16	2.08	2.08
108 9/6					6.055	2.045	6.32	2.065	6.065	2.08	6.18	2.06	2.062
109 10/6					6.03	2.07	6.30	2.085	6.05	2.095	6.17	2.07	2.08
111 12/6					6.035	2.065	6.30	2.085	6.04	2.105	6.155	2.085	2.085
112 13/6					6.015	2.085	6.285	2.10	6.02	2.125	6.14	2.10	2.102
113 14/6					6.02	2.08	6.275	2.11	6.03	2.115	6.145	2.095	2.10
114 15/6					6.005	2.095	6.265	2.12	6.01	2.135	6.12	2.12	2.118
115 16/6					6.005	2.095	6.27	2.115	6.02	2.125	6.13	2.11	2.111
116 17/6					6.01	2.09	6.27	2.115	6.02	2.125	6.125	2.115	2.111